Development of a Manufacturing Strategy for a Low Investment, Bent Tube Space Frame Vehicle in North America

By

Gregory T. Webb

B.S. Mechanical Engineering, The Ohio State University 1998

Submitted to the Sloan School of Management and the
Department of Mechanical Engineering in partial fulfillment of the
Requirements for the degrees of

Master of Business Administration
And
Master of Science in Mechanical Engineering

In conjunction with the Leaders for Manufacturing program at the
Massachusetts Institute of Technology
June 2003

Signature of Author ____

Sloan School of Management
Department of Mechanical Engineering
May 9, 2003

Certified by ____

Thomas Roemer
Assistant Professor of Management Science
Thesis Supervisor

Certified by ____

Dr. Daniel Whitney
Senior Research Scientist, MIT Ctr for Tech, Policy and Industrial Development
Thesis Supervisor

Accepted by ____

Margaret Andrews
Executive Director of Master's Program
Sloan School of Management

Accepted by ____

Ain Sonin
Chairman, Departmental Committee for Graduate Students
Department of Mechanical Engineering

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ABSTRACT

The North American automotive market has become increasingly segmented in recent years with an abundance of "niche" vehicles and increased competition from foreign transplant companies. Because of this increased segmentation, typical production volumes per model have decreased. The number of models that sell in the three or four hundred thousand units per year range continues to decrease. These reduced volumes require that automotive manufacturers find a way to reduce the required investment to bring a new product to market and mass produce it.

This thesis develops a manufacturing strategy for producing a low volume vehicle in North America using a bent tube space frame architecture. The body panel processes are chosen from a variety of materials and processes based on panel properties, investment and part costs. The framing operation and body panels are tied together in a process sequence. Overall investment figures are calculated for the plant and manufacturing system.

This thesis determines that a pure bent tube space frame is not the most effective way to achieve low investment manufacturing in North America, although it may be profitable utilizing the Mexico labor market. This type of architecture is more appropriate as part of a global strategy involving developing markets. This type of space frame architecture could be used to enable increased manufacturing flexibility and could be more appropriate for North American use if combined with other technologies such as hydroforming.

Thesis Advisor: Dr. Daniel E. Whitney, MIT School of Engineering
Prof. Thomas Roemer, Sloan School of Management

Acknowledgements

First, I would like to thank the Leaders for Manufacturing (LFM) program at MIT for the incredible learning opportunity that they have provided me with. The seven-month internship at General Motors was just one of the many components of what has been a life-changing experience. The LFM network of faculty, staff, students and alums has provided me with a very supportive network of teachers, colleagues and friends. In particular, I expect that the bonds I have formed over the last two years with my classmates and friends will continue to grow for a long-time to come. I have learned so much from their rich, diverse backgrounds and look forward to sharing more experiences with them in the future.

I would also like to thank the General Motors Corporation for their continued support of the LFM program. Their generous sponsorship of my internship project allowed me to begin applying some of what I have learned at MIT and continue the learning in a real business environment.

I could not have completed this project without the support of so many people at General Motors. My supervisors, Chris Williams and BJ Lee, helped guide me through the entire process and ensured that I had access to all of the necessary resources. I would also like to thank Cara W., Kathleen D., Len B., Phil D., Dan C., Ray K., Mike R., Bob A., Hamid K., Theresa L., Joe H., my classmate and fellow intern Kristin and the many others that provided their support and expertise every time I needed it. There were so many within GM that had a part in making this project a success that I cannot possibly list them all here. I hope everyone realizes how much I appreciated his or her support.

I would also like to thank my MIT thesis advisors, Professor Thomas Roemer and Dr. Daniel Whitney. Their support and expert guidance helped me get through both the internship project and the writing of this thesis. Their experience helped provide me with direction throughout the entire process.

The author would like to note that some data for this thesis has been modified or disguised to protect confidentiality concerns of the host company. Those edits have been made such that the conclusions remain consistent with the original data.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1 - INTRODUCTION

1.1 Industry Background

The North American automotive market has become increasingly segmented in recent years with an abundance of "niche" vehicles and increased competition from foreign transplant companies. The lines that used to separate distinct product segments have become blurred by the presence of more and more hybrid, or crossover, vehicles. Because of this increased segmentation, typical production volumes per model have decreased. The number of models that sell in the three or four hundred thousand units per year range continues to decrease. These reduced volumes require that automotive manufacturers find a way to reduce the required investment to bring a new product to market and mass produce it.

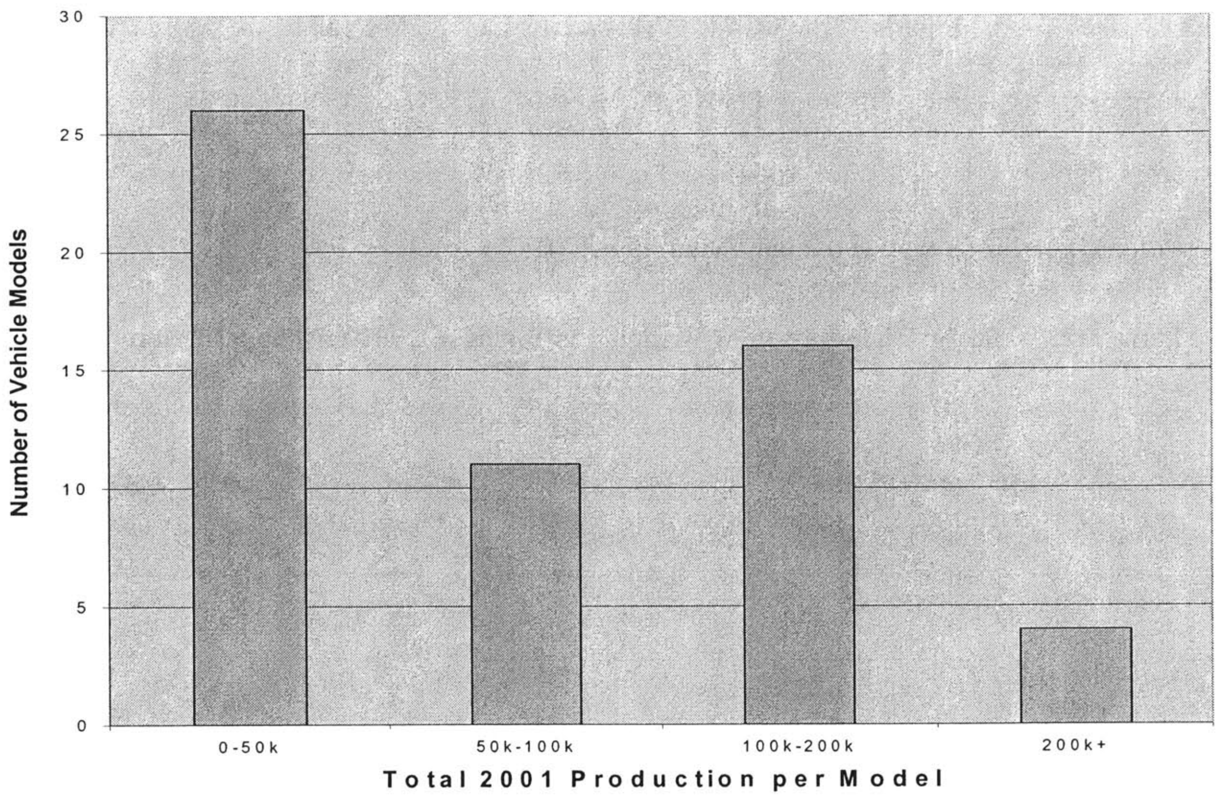
In the 1980's there were only a handful of sport utility vehicles on the market and they were basically one of two different sizes. Compare that to today, where there are over sixty-five sport utility models available as 2003 models in the United State. For almost any size of SUV a consumer could want, they will find themselves with at least a few different options. In that same amount of time, the selections of cars and trucks have also increased. The total volume of vehicles sold in the US has increased only slightly. In total, there are more than 275 car, truck, van, SUV, and crossover models for sale in 2003. With total sales of 16.8 million vehicles in the US in 2002, that's an average of just over 60,000 units per model. The number of models on the market has increased by 10% over the last decade and market forecaster Global Insight predicts it will increase by another 6% within the next four years.

1.2 Company Background

General Motors (GM) is the world's largest automotive manufacturer and currently has a worldwide market share of over 15% and a US market share of over 28%. GM vehicles in the US are sold under the brand names of Buick, Cadillac, Chevrolet, GMC, Hummer, Oldsmobile, Pontiac, Saab and Saturn and there are over 60 GM models available as 2003 models. With 2002 US sales of approximately 4.7 million vehicles, GM's average production is approximately 78,000 units per model.

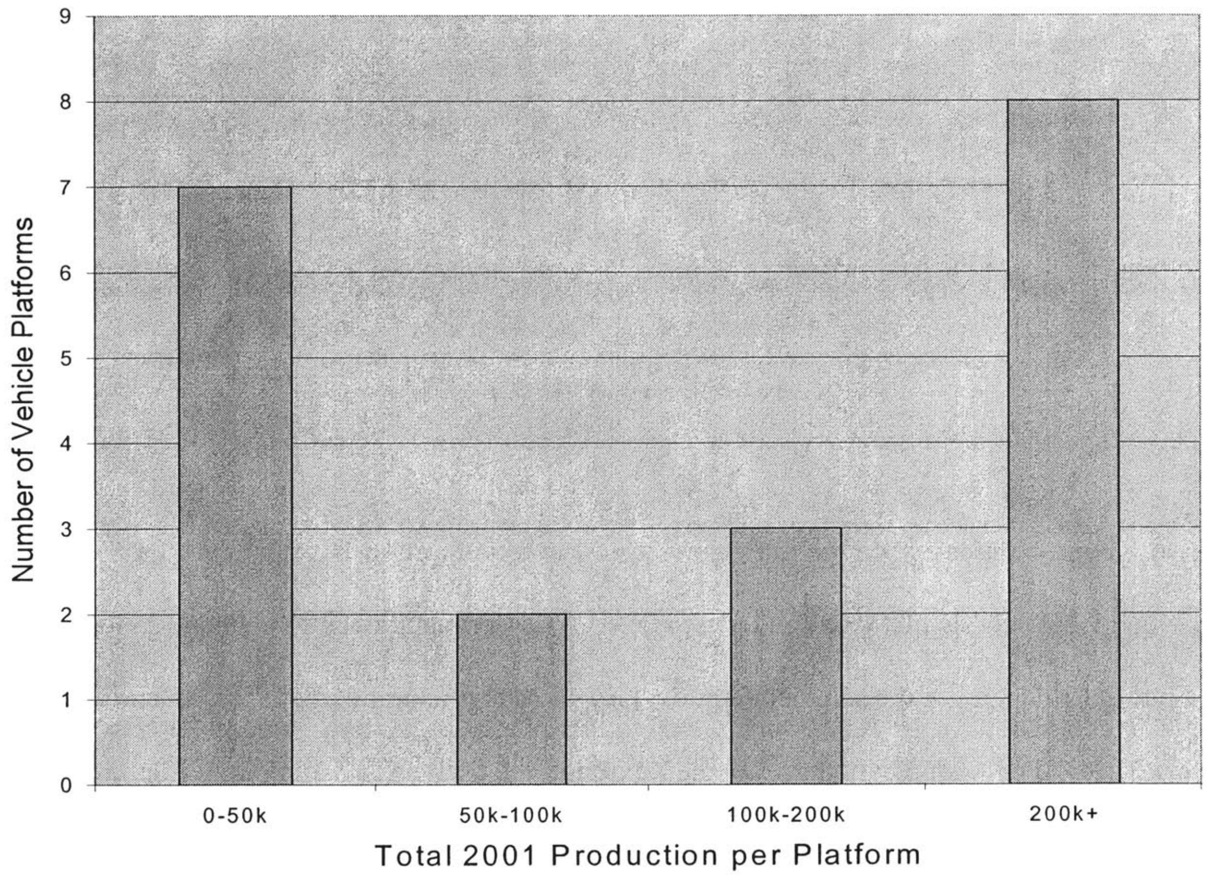
Figure 1-1 below shows the range of production volumes for GM models that were produced in 2001. The chart shows that there were 26 GM models produced in volumes of less than 50,000 units in 2001. Almost half of the total models were produced in what most people would consider low volume for automotive production. There were 11 models produced in volumes of 50,000-100,000, 16 models produced in volumes of 100,000-200,000 and 4 models produced in volumes greater than 200,000. A complete list of GM models manufactured in North America in 2001 and their production volumes can be found in Appendix 1. The largest volume product, by far, was the Chevrolet Silverado with 2001 production of more than 700,000 units. Its GMC sibling, the Sierra, had 2001 production of more than 200,000 units using many of the same parts. It's important to note that a few of the models produced in 2001 were not produced for the full year, since they were old models being phased out or new models that began production mid-year.

Figure 2-1: Volume Distribution of Vehicle Models in 2001 GM Production



To deal with these decreasing production volumes, GM in recent years has increased their emphasis on global vehicle platforms and parts reuse. A platform approach to vehicle manufacturing uses many of the same underbody, chassis and structural components to build multiple vehicles. For example, underneath their exterior, the Chevrolet Camaro and Pontiac Firebird have a lot of parts commonality between them. This makes it much easier to manufacture them on the same assembly line and reduces the number of tools and total tooling investment required. Only 27,108 Camaros were produced in 2001, along with 20,281 Firebirds. However, that means there were 47,389 cars produced using many of the same tools and parts. There are many other examples of parts sharing strategies within the GM portfolio and in recent years it has taken on more of a global emphasis. GM is focused on leveraging its global size by developing vehicle platforms that can be used not only for its US models, but also for brands and models that it sells in other parts of the world. If several distinct models can be designed from one common platform, some of the tooling investment costs and development costs can be spread across much larger production volumes. Figure 1-2 shows the range of production volumes for GM platforms that were manufactured in 2001.

Figure 3-2: Volume Distribution of Vehicle Platforms in 2001 GM Production



This platform strategy can also enable more plant flexibility and allow more models to be manufactured on the same production line with reduced investment. Vehicles built off of the same platform are typically built using the same processes, have similar sizes and share some of the same body shop tooling. The main differences between the models come from the body panels that provide its exterior styling and components assembled to a completed body to provide the desired performance and functionality. Effective use of global vehicle platforms can reduce GM's manufacturing plant and tooling investments, especially in the body shop area.

As can be seen in the figure, the platform volumes paint a very different picture than the model volumes. There were seven vehicle platforms produced in volumes under 50,000 units and three of those were because they were new platforms, just beginning production during 2001, or old platforms, being phased out mid-year in 2001. At the other end of the spectrum, there were eight platforms that were produced in volumes greater than 200,000 units. The largest volume platform by a large margin was the CK platform with over 1.5 million vehicles produced in 2001. GM had nine full-size pickup and SUV models built off of the CK platform in 2001. However, there is limited commonality across the entire CK family. Although they are all considered the same platform, they are built on several different frames to provide a variety of lengths, wheelbases, and load ratings. There are also a variety of drive trains, suspensions and other components. There are limits to how much common tooling can be used across a vehicle platform while still allowing for each model to be unique and targeted at a different market.

GM North America's (GMNA) headquarters are in Detroit, Michigan. A majority of the vehicle design and development work for GMNA vehicles is performed at the Technical Center campus in Warren, Michigan, with several thousand GM employees also located at a campus in Pontiac, Michigan. GM's North American vehicle production takes place at over 30 different plants. While most are located in the United States, there are a few in Canada and a few in Mexico.

1.3 Organizational Structure

This project was completed while working at General Motor's Technical Center in Warren, Michigan. The author worked in the Advanced Vehicle Development Center (AVDC) in the Manufacturing Engineering organization, which reports up through the Vice President of Vehicle Operations. This organization is responsible for the manufacturing engineering work for products that are in the very early stages of development. They work very closely with individual functional areas to gain a full understanding of how a vehicle will be manufactured if it is developed. They work with other experts as the team develops manufacturing process details, plant layouts, investment estimates, headcount estimates, etc.

The author was not a member of an existing team, but did work with members from a variety of other teams. The project supervisor was a Manufacturing Integration Manager in the AVDC Manufacturing Engineering department.

1.4 Project Description

The goal of this project is to develop a low investment manufacturing strategy that will help GM adapt to the decreasing model volumes in the North American automotive market. Everyone has their own idea of what defines "low volume" manufacturing, but for this thesis low volume automobile manufacturing is considered to be 50,000 units per year or less. The manufacturing strategy developed will be geared towards building a family sedan with annual volumes of fewer than 50,000 units, which is not much less than GM's current average production of 78,000 units per model.[1]

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[1] "Sedan" is a general term for a car that has a front and rear seat as well as a permanent roof. It typically has 4 doors and seating capacity for 4 or 5 persons.

The manufacturing strategy is based on North American production using a bent tube space frame architecture, which is a different structure than most mass-produced vehicles today. This project looks at how that bent tube space frame should be manufactured, how it compares in cost to more traditional architectures, as well as what types of advantages and disadvantages it presents.

Along with the frame construction, this project also looks at the body panel alternatives that could be used to complete assembly of the vehicle. It focuses on a few of the more non-traditional composite alternatives to explore how they might be used to enable this type of low volume vehicle program.

The manufacturing strategy is intended to be for production in North America. For that reason, the project looks at production in the United States as well as production in Mexico. The two countries have very different labor markets, so this project will take a look at how those labor differences affect the manufacturing strategy. As another point of comparison and in order to consider a global strategy, it will also look at implications of executing this type of program in a Far East country where labor rates are significantly lower than Mexico.

1.5 Thesis Overview

A brief summary of the subject covered in each chapter is as follows:

Chapter 1 provides some background for this thesis project. It provides background on the industry and company and explains part of the motivation for this project. It then explains the project purpose and goals.

Chapter 2 discusses vehicle architectures. It will describe the three basic categories of vehicle architectures and will compare and contrast them. It explains the motivation behind choosing a bent tube space frame architecture.

Chapter 3 provides a manufacturing process overview for constructing a bent tube space frame vehicle. It shows the overall manufacturing plant flow and provides some detail for the activities within each area.

Chapter 4 describes the materials and manufacturing processes considered for constructing the body panels. It provides some technical background for each process and discusses some of the advantages and disadvantages. The chapter ends with an overview of the financial analysis for each material strategy and selects the optimal strategy.

Chapter 5 details the conclusions drawn from this project. It details the conclusions drawn about the viability of bent tube space frame vehicles in the US and Mexico. It also touches on how things might be different in developing countries of the Far East and what this all means for a global low investment strategy for GM.

CHAPTER 2 - VEHICLE ARCHITECTURE

2.1 Traditional Stamped Architecture

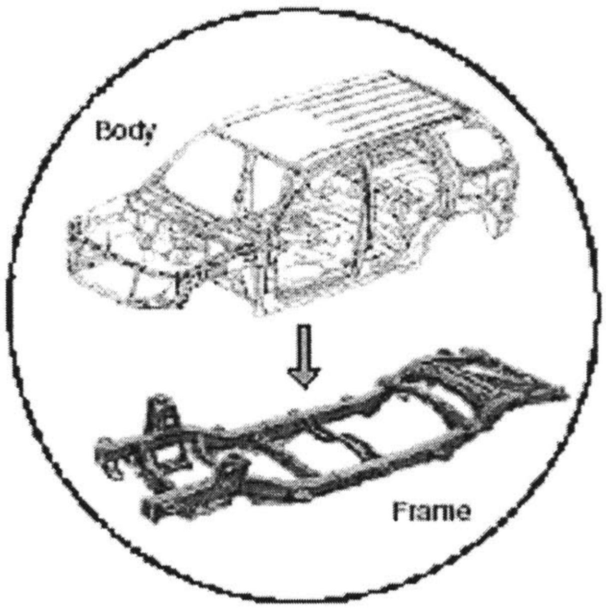
Three primary architecture types are used to build passenger vehicles. The term architecture in this setting is used to describe how the chassis is designed to provide structure. What type of basic topology is used to provide the vehicle with its shape, strength and closure? Most passenger vehicles on the market today are designed using either a body-on-frame (BOF) or body-frame-integral (BFI) architecture. The third architecture type, which in its purest form is typically not used for mass production vehicles, is a space frame. This space frame construction is the one explored for this thesis. However, for comparison purposes, a brief description of BOF and BFI construction will also be provided.

2.1.1 Body-on-Frame (BOF)

BOF architectures were originally used for all cars and are used today for most trucks, full-size vans and large sport utility vehicles. The underlying steel frame provides a large portion of the strength for BOF vehicles. A BOF frame typically consists of two frame rails, running the length of the vehicle, connected at multiple points with frame members running across the width of the vehicle. Figure 2-1 below shows a typical BOF frame as well as the body that might be mated to it. The engine, transmission, suspension, steering, bumpers, etc. are attached directly to this frame. The body of the vehicle is traditionally designed using stamped metal parts that are spot welded together. In increasingly more cases, alternative materials such as composites and aluminum are being used for some or all of these body panels.

In a BOF vehicle, the body itself does not have to be designed to provide all of the strength and rigidity because it can rely on the heavy-duty frame to provide most of the torsional rigidity as well as the strength for front end or rear end collisions. This structural frame can then be used for other models as well, spreading the investment costs across a larger volume of vehicles. Each model is made unique by having a different body mounted onto the frame.

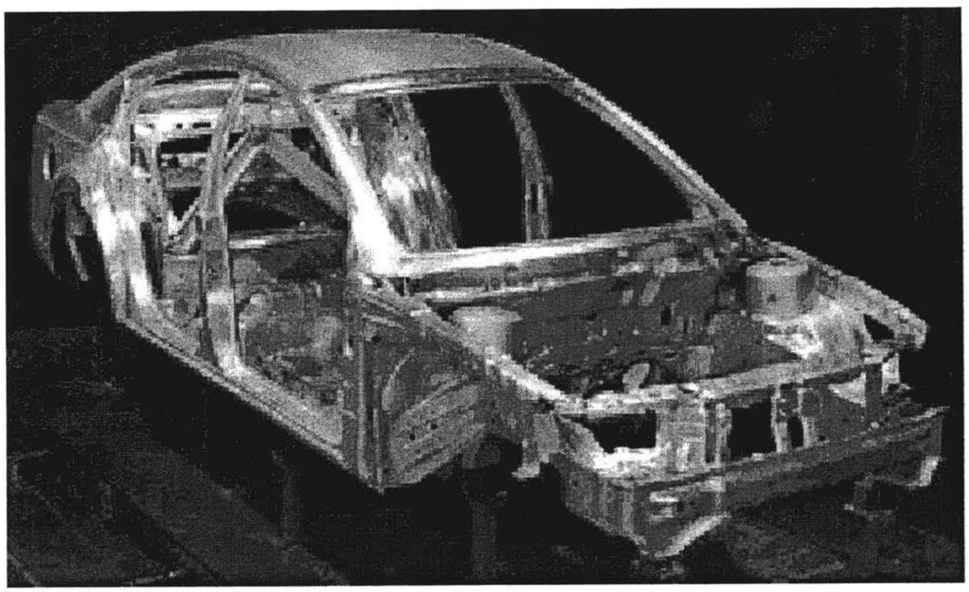
Figure 2-1: Body-on-Frame Architecture



2.1.2 Body-Frame-Integral (BFI)

BFI architectures are used for most passenger cars, mini-vans and small sport utility vehicles on the market today. Many people also refer to the BFI structure as a unibody (unitized-body) vehicle. This BFI structure differs from the BOF structure in that it does not have a separate frame underneath the body. Figure 2-2 below shows a BFI constructed vehicle. The stamped panels are designed to provide all of the necessary strength and rigidity for the completed vehicle. The engine, transmission, suspension, steering, etc. is bolted directly to stamped body panels. While steel has been by far the most widely used body panel material, the use of composites for selected panels as well as the use of aluminum has begun to gain some momentum. Jaguar's 2004 XJ is an example of a car that has been built with an all aluminum body, although the higher cost and some processing issues still make it prohibitive for more frequent use on all types of car models.

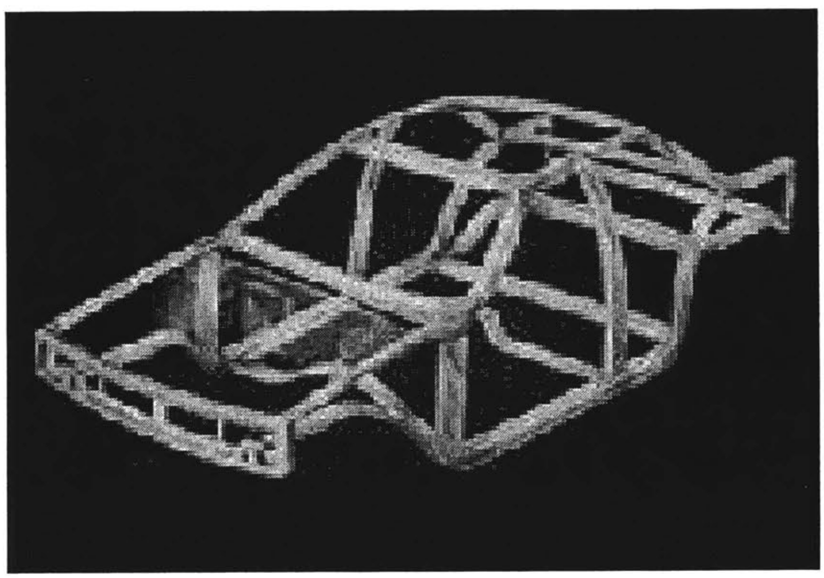
Figure 2-2: Body-Frame-Integral Architecture



2.2 Space Frame Architecture

A tubular space frame construction can be thought of as being similar to a birdcage, or similar to the way that a house is built. In house construction, the strength of the building is provided by a series of two-by-fours and other boards, fastened together to form a cage-like structure. Panels such as insulation and drywall are then attached to this wooden frame to provide the house with closure and separate the interior from the exterior. In a space frame vehicle, the strength and rigidity of the vehicle is provided by a set of structural tubes, which are fastened together by welding or mechanical fasteners to form a similar cage-like structure. The frame members are designed and connected so that they are loaded primarily in tension and compression. The engine, transmission, suspension, steering, etc. are mounted directly to structural members of the space frame. Body panels can then be mounted onto this space frame structure to provide it with closure to block out the weather, wind, debris, noise, etc. Figure 2-4 below shows a typical space frame structure.

Figure 2-3: Space Frame Architecture



Tubular space frame construction is used in some specialty and super low volume products, such as race cars, monster trucks and Lamborghini's, but is typically not used for mass produced vehicles.

All of the body panels for the car are mounted to the finished space frame pictured above. There are exterior body panels that provide the car with its exterior surface and appearance. There are also interior body panels that close out the interior of the car from the frame. Depending on how the frame is designed and how the body panels are manufactured, a completed car may require 25 to 40 panel part numbers. For analysis purposes in this thesis, it is assumed that the car being manufactured requires 30 panel part numbers. Appendix 1 provides a list of the parts that are included.

2.3 Architecture Comparison

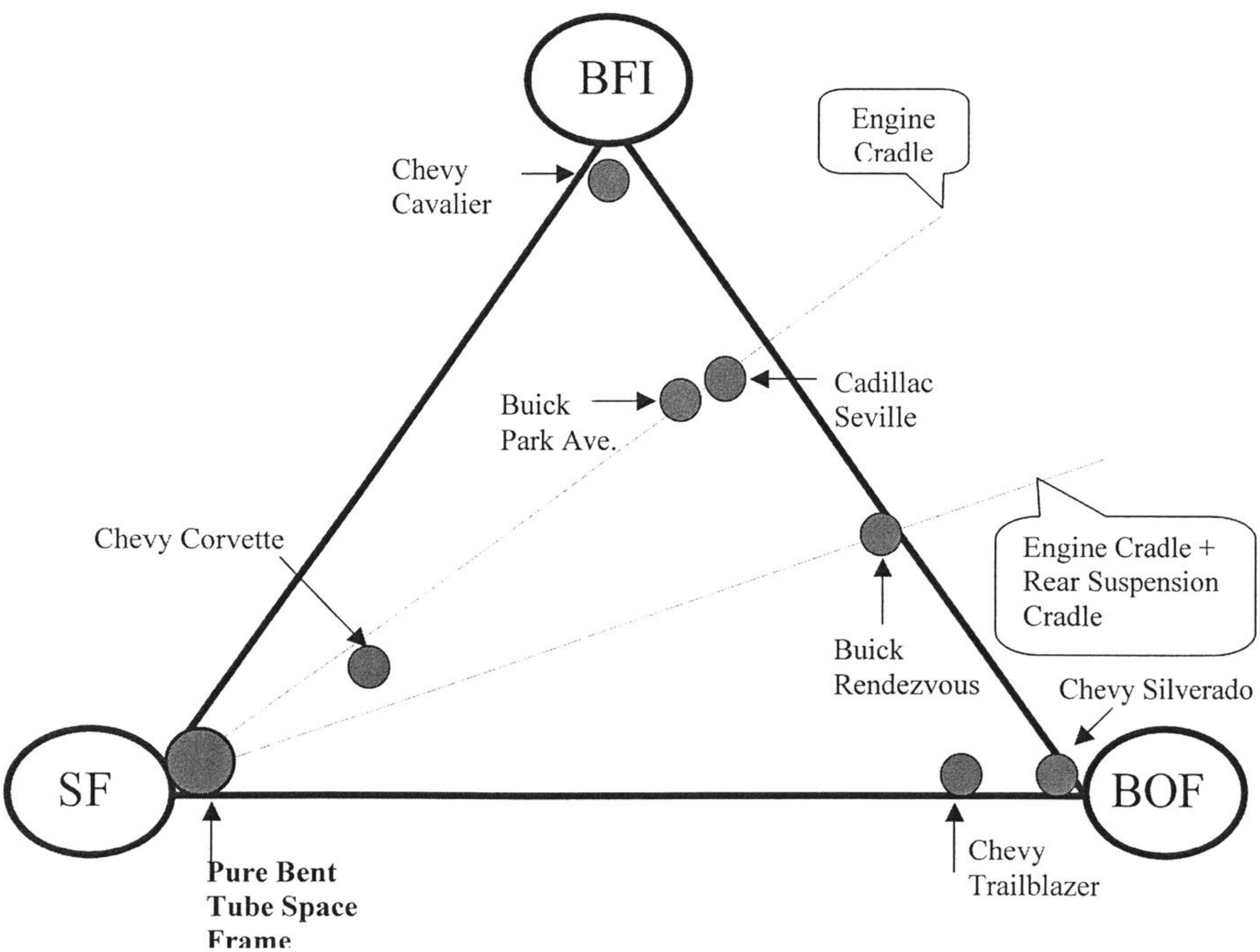
While most automotive engineers would agree that there are three basic types of vehicle architecture, classifying individual models into one of the three categories is not always a clear-cut decision. Many vehicle designs blend characteristics from more than one category. Figure 2-4 below depicts the range of architectures and shows where some current models would fit on the continuum.

As indicated in the figure, there are two main variations on the BFI design that bring it closer to the BOF architectures. One of the variants is a BFI type body structure with an engine cradle. The other variant is a BFI type body structure with both an engine cradle and a rear suspension cradle.

Two primary frame rails that extend from the front end of the body form an engine cradle. The front bumper, engine, steering, and front suspension are then mounted to this engine cradle. The front end is built similar to a BOF vehicle, while the rest of the car is built like a typical BFI car. The Buick Park Avenue and Cadillac Seville both use this type of structure.

The rear suspension cradle is the same basic concept as the engine cradle. It consists of two primary frame rails extending from the rear of a BFI type body. The rear bumper, suspension and brake components are mounted to this rear suspension cradle. Cars built with a rear suspension cradle also typically are designed with an engine cradle. The front and rear ends are both built similar to a BOF vehicle, while the rest of the car is built like a typical BFI car. This type of body structure is used for the Buick Rendezvous.

Figure 2-4: Vehicle Architecture Varieties



Of the vehicles shown in Figure 2-4, the Chevrolet Corvette is the closest thing to a space frame architecture. In some areas it does have a cage-like structure. However, it also has a touch of both BFI and BOF architectures in its design. It relies on stamped parts to provide strength and structure in some areas, similar to BFI. It also has two main frame rails that run the length of the car and provide a lot of its strength and rigidity, similar to BOF. The Corvette's hydroformed frame rails differ from a true BOF in that the body does not sit on top of them. The rails are integrated into the body design and run through the structure in some areas.

One of the main benefits of space frame construction is that it requires a lower up front investment. A significant portion of body shop investment for BOF and BFI vehicles is for the body panel stamping dies. Since a space frame car requires a greatly reduced number of stampings, this stamping die investment is also greatly reduced. How much the stamping die investment is reduced depends greatly on what type of body panels are used. This thesis explores a few of the body panel alternatives and the resulting investment reduction in later sections.

Another potential benefit of space frame construction could be in product design flexibility. The underlying frame structure provides all of the strength and rigidity for normal vehicle performance as well as crash worthiness. The main purpose of the body panels, both interior and exterior, is to provide closure. The shape and contours of the body panels can also be used to define the styling of the vehicle. Due to this fact, some styling variety can be achieved more easily by hanging panels with different contours on the same underlying frame structure. This could make the development of these alternate styles a much easier and cheaper process. In stamped BFI vehicle, the body panels provide the closure and styling, but they also contribute significantly to the structure of the vehicle. Therefore, a change to the styling of the body panels requires significant testing to ensure the resulting structure still meets all of the performance requirements. However, if a space frame construction is used and the styling changes are done solely through different contours on the non-structural body panels, it could require a reduced amount of performance testing and savings in the millions or tens of millions of dollars range. In Chapter 3, this thesis will explore some of the process details for the space frame construction. From these process details, a couple of basic conclusions can be drawn about the manufacturing flexibility compared to stamped BFI architectures.

A couple of the drawbacks for bent tube space frame construction are that it has a higher part count and requires more labor. Because of the higher part count, a huge amount of welding has to be done to join components together. In fact, the space frame for a small family sedan could require as much as 50 meters of welding. Welding these frame components together also requires a large number of body shop fixtures to locate and hold the pieces in place.

Hydroforming is a process that could be used to create space frame structures that are not quite as labor intensive and have a much lower part count.[2] With hydroforming, frame components can be designed to have more complex geometries, so that fewer parts are needed. They can also be designed to include locating features so that fewer fixtures are needed in the body shop.

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[2] Hydroforming is a process of shaping steel tubes through the application of water at extremely high pressure. It replaces traditional stamping processes, preserving more of the steel's strength and stiffness as it goes through the forming process. It is performed at low temperatures to retain optimal material properties, resulting in high strength and stiffness, relatively low weight, precise quality and reduced material usage.

However, for this thesis, hydroforming was not considered as an option. The goal of this project was defined as developing a manufacturing strategy for a pure bent tube space frame vehicle. Hydroforming does require significant tooling investment, so maintaining a pure bent tube construction is an attempt to minimize the overall manufacturing investment.

2.4 Chapter Summary

This chapter has defined and described the three main types of architectures that can be used in vehicle manufacturing: BFI, BOF and space frame. It described when and where each of the architecture types is typically used and then compared the advantages and disadvantages of using a space frame.

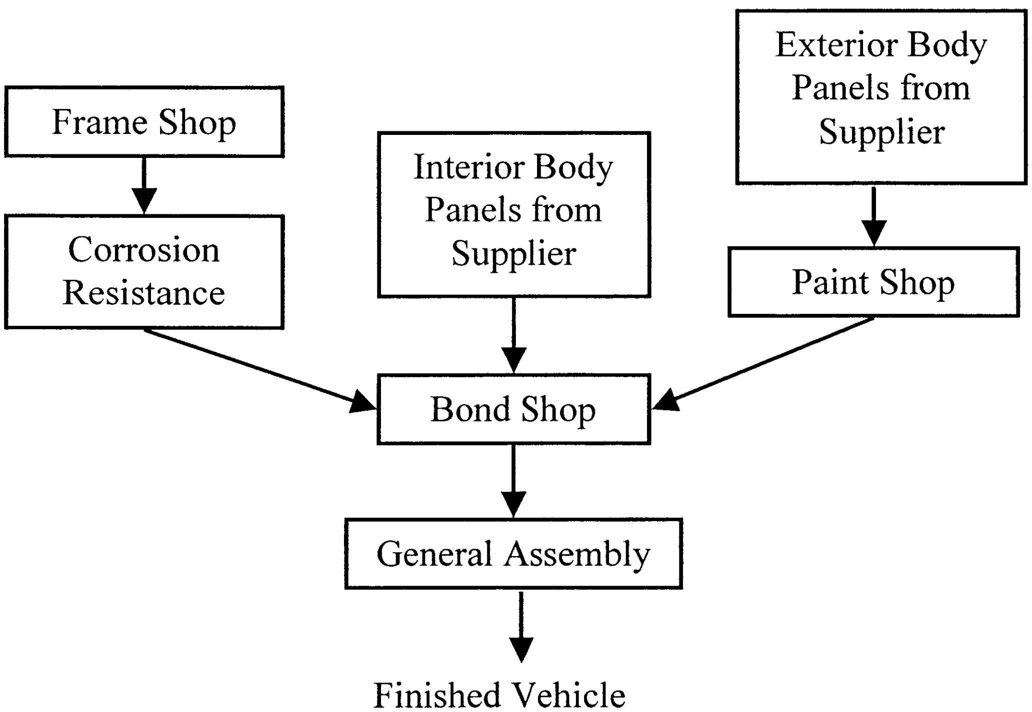
The following chapter will explore the manufacturing process for a bent tube space frame vehicle. It describes the overall assembly plant process and provides a more detailed process sequence description for those processes that may be unique to using a bent tube space frame.

CHAPTER 3 – MANUFACTURING PROCESS

3.1 Assembly Plant Process Flow

The overall assembly plant process flow for building a bent tube space frame vehicle is similar to traditional plants, but there are a couple of significant differences. Figure 3-1 below shows this overall process flow.

Figure 3-1: Assembly Plant Process Flow



The space frame structure is fabricated in the frame shop. The finished frame then goes through a corrosion resistance process before being sent to the bond shop. In parallel to that frame activity, the body panels arrive from their respective suppliers. The exterior body panels may require painting, but the interior body panels do not. After the panels are finished, they are also sent to the bond shop. In the bond shop, the body panels are assembled to the frame to form the completed body. The combination of the frame shop and bond shop take the place of what is referred to as the body shop in more traditional automotive plants. As is detailed in Sections 3.2 and 3.3, the frame shop and bond shop both utilize very manual processes. Because of that, the combined headcount for the frame shop and bond shop is expected to be three times as large as the headcount for an equivalent BFI body shop. After exiting the bond shop, the body passes on to the general assembly area, where all of the vehicle's contents and accessories are assembled to it.

As can be seen in this Figure 3-1, the interior body panels and exterior body panels would probably not come from the same source. They could be made of different materials and come from different suppliers. The body panel possibilities are explored further in Chapter 4 of this thesis.

Once the frame structure is completed, it has to go through some type of corrosion resistance process so that the metal can survive out in the environment for the life of the car. Because the frame will not be visible in the final car, it is not necessary that it be painted. In fact there are other processes available that provide the necessary corrosion protection but are not nearly as expensive as a paint shop, one of which is examined in further detail.

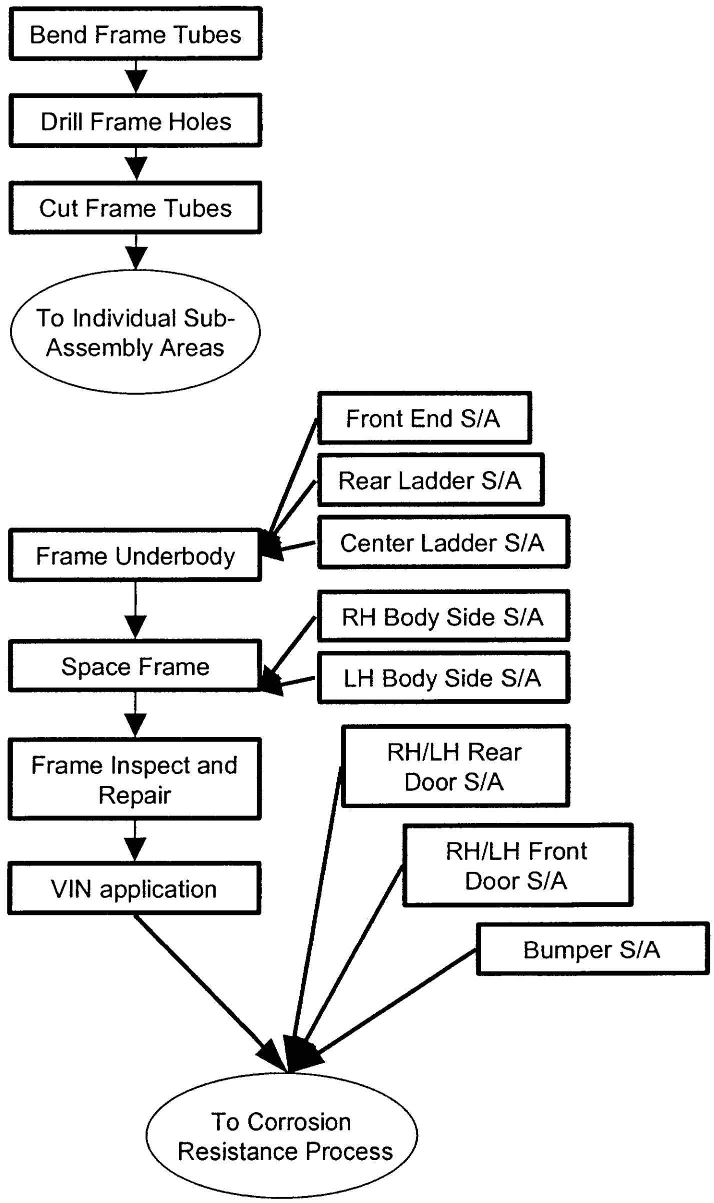
For this type of application, a steel tube space frame is sent through a process such as Henkel Surface Technologies' Autophoretic® coating. This coating process provides the steel with a corrosion resistant surface finish that will enable it to survive years of weather exposure. The Autophoretic® coating process is a dip process, similar to what traditional paint shops use, but it is much cheaper and requires a smaller footprint. The investment for an Autophoretic® coating system for low volume car manufacturing is in the one to two million dollars range. A typical automotive paint shop, even for low volume production, could cost seventy to one hundred times that amount. The Autophoretic® coating does not provide the proper surface for automotive painting, but painting of the space frame is not necessary. Body panels, both on the interior and exterior, cover the steel tubing. Because only the body panels have to be sent through the paint shop, a lower volume paint shop can be used to save investment or the panels can be painted outside the plant. BOF and BFI architecture vehicles are sent through a traditional paint shop after the body and frame construction has been completed, so all appropriate parts are painted at one time and more paint shop capacity is required.

3.2 Frame Shop Process Detail

The frame shop is where the space frame structure is constructed. The inputs to the frame shop are the raw materials, which in this case would be rectangular steel tubing of various sizes and gauges as required by the vehicle design, and the output is a finished frame ready to have the body panels installed. All of the joining is performed using manual MIG welding.

Figure 3-2 shows the process sequence for this frame construction. The basic flow of this type of frame shop is fairly simple. The raw steel tubes are cut to length, have the necessary holes drilled into them and are bent to the proper angles. These finished steel tubes are then sent to the appropriate subassembly areas.

Figure 3-2: Frame Shop Process Sequence



The frame shop layout has one main line that is fed by five subassembly lines. The underbody of the frame is built up in three subassemblies: front, middle and rear.[3] These three subassemblies are connected together into one part before being joined with the body-sides.[4] Each of these body-sides is also built up as a separate subassembly before being fed into the main line.

In a low volume environment, it is appropriate for this frame shop to have no powered conveyance. The part needs to be stationary while it is being welded in order for the operators to complete safe, consistent welds. Parts can be moved along each of the subassembly lines using a simple ceiling mounted hoist. An operator can grab the part with the hoist, lift it from its current station and carry it forward to the next station before setting it down again. At the limit of our low volume definition, a plant is producing 50,000 units per year. Using a 2-crew/2-shift operation, that requires a running throughput of approximately 14.6 jobs per hour (jph).[5] That equates to a station cycle time of just over 4 minutes. This hoist and carry process would typically take 5 to 10 seconds to complete, which makes up a very small percentage of the time it spends at each station. The investment to add a powered conveyance line would be in the tens of millions of dollars and would not be worth the cost. Each workstation would have approximately 4 minutes to perform their required tasks and approximately 10 seconds to transfer the part to the next station. At lower levels of production, each station would have even longer to complete their tasks while still requiring the same amount of time to transfer the part. If the production rate were changed significantly from the original design rate, the line would be

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[3] The underbody of the vehicle refers to surfaces underneath the car where the suspension, brakes, gas tank, wheels and other chassis components are mounted.
[4] The body-sides refer to the parts that extend from the front fender back to the tail end of the car and encircle the door openings.
[5] For 2-crew/2-shift operation, a plant operates for two 8-hour shifts per day, with one crew working the day shift and one crew working the night shift. This provides the plant with 80 hours of operation per week without overtime.

redesigned and rebalanced to keep the number of stations and workers to a minimum while having the appropriate workload at each station.

All of the joining in the frame shop is performed using manual MIG welding. Each of these joints will have four possible sides that can be welded, but in most cases the entire perimeter of the joint will not be welded in one station. When the joint is initially formed in one of the subassembly jigs, there will be one side that is facing down towards the ground. That side is not easily accessible or viewable by the operators in that station. Therefore, that side is welded further down the manufacturing line in a different station, after the frame has been flipped over to provide better accessibility.

Once the body-sides come together with the underbody, the basic size and shape of the space frame is complete. At that point, the structure is too large to easily pass from station to station using a simple hoist and carry method. It has to be set onto a cart that can then be manually pushed through the rest of the manufacturing line. The plant floor is lined with a very simple track to guide the cart and after operators have completed their station's tasks they can push the cart forward to the next station.

The underlying frame for the doors and other closures are built in separate cells away from the main line. They are built using the same types of processes with MIG welding and hoist and carry conveyance. They are sent to the autophoretic® coating and bond shops with the vehicle frame, but they are not attached until later in the assembly process.

To minimize the manufacturing investment, all of the framing is designed to require bends in only one plane. This greatly decreases the complexity and cost of the bending equipment needed. It also makes the check fixtures and quality control cheaper because it is easier to only have to measure a part for accuracy in a single plane.

The welding fixtures in the frame shop are constructed using all manual clamping. The fixtures can serve a double purpose as both weld fixtures and check fixtures. If all of the clamps cannot be locked into place, this would indicate that parts are missing or are out of place. However, wear of the clamp surfaces will affect the accuracy of these check fixtures and must be monitored closely. Much of the quality assurance will also rely on visual inspection by the workers.

These welding fixtures are dedicated to one particular frame design. If multiple frame structures are manufactured on one assembly line, they require multiple welding fixtures. Each welding fixture requires a significant number of clamps and locating surfaces. Therefore, there is not enough room to have the clamps and locating surfaces for multiple frame designs on one fixture. Movable clamps and locating surfaces are not a viable option either. Manual movement of the clamps takes too long and does not provide the accuracy needed for consistent, dimensionally accurate frames. Robotic movement of the clamps may have similar problems and also requires too many additional pieces on the welding fixture. This would limit access to the joints and hinder the workers' ability to complete the MIG welding. The robotically adjusting clamps also add significant cost when used in the large quantities that would be needed.

This frame shop does increase manufacturing flexibility due to the fact that there are no monuments needed in the space frame fabrication process.[6] Each of the welding fixtures can be built on a wheeled structure. This allows the fixtures to be pushed out of the manufacturing line so that they can be replaced with a similar fixture for a different frame design. The flexibility is limited though, since the different product varieties have to be built in fairly large batches to reduce the number of tooling changeovers and time spent rolling fixtures around. The plant cannot afford to spend a great deal of their time moving the large tooling fixtures around and setting up between frame models.

3.3 Bond Shop Process Detail

The bond shop is where the space frame and body panels are assembled together. The bond shop receives a completed space frame from the autophoretic® coating process and completed body panels from the panel suppliers. The body panel material strategy is discussed in detail in Chapter 4. Parts fabrication is typically not performed in a vehicle assembly plant. A nearby supplier fabricates the panels. In the case of steel body panels, that supplier could be GM's Metal Fabrication Division. In the case of composite panels, that supplier is most likely an outside company that maintains composite technologies as their core competency.

Like the frame shop, the bond shop also used no powered conveyance. The space frame stays on the cart that it was placed onto near the end of the frame shop line. Using this cart, operators can push the car from station to station. As in the frame shop, the car needs to be stationary during the panel bonding process. Therefore, a continuous moving line would not be appropriate. A

[6] A monument is defined as a large, permanent piece of manufacturing equipment that cannot be easily moved to change the production floor layout.

stop-station powered conveyance line is not worth the investment in this type of low volume, low investment application and is not necessary.[7]

A basic process sequence for the bond shop is shown below in figure 3-3. As shown in this process sequence map, multiple panels can be bonded onto the car at one time. For instance, the mainline starts off with all of the underbody parts being bonded on in one station. The wheel arches, floor pan, rear pan and bulkhead (dashboard) are all bonded on in one station using one fixture. The bonding fixture provides locating datums for the panels as well as the space frame, to ensure that the panels are positioned correctly on the car.

The doors and other closures are built up in a similar manner on separate lines. The door line in the bond shop receives a bent tube structure from the frame shop. This structure is sandwiched between the door inner and outer panels in a bonding fixture. The other components, such as the window, handles, lock mechanism, etc. are assemble into place before the door panels are bonded together.

For most of the bonding stations, duplicates of the bonding fixtures would be required to meet the plant's desired throughput. Development work would be required to determine the optimal bonding adhesive to use, based on the material chosen for the body panels. However, in similar bonding processes, it is not uncommon for the adhesive to be an epoxy that requires 7 to 10 minutes set time before it can be removed from the bonding fixtures. If the plant is producing

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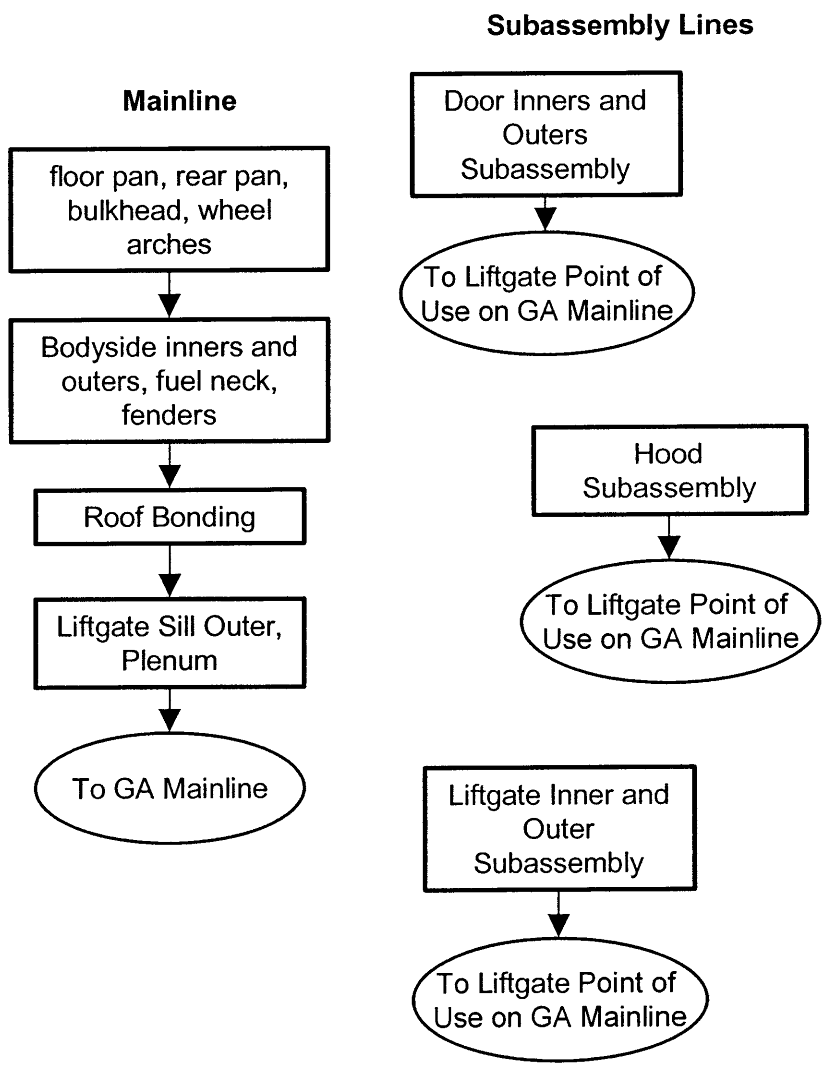
[7] A stop-station conveyor is one that advances parts rapidly between stations and then has a set dwell time at each station before advancing them on again.

50,000 units per year, with a station cycle time of just over 4 minutes, it requires 2 or 3 of each bonding fixture to achieve the required throughput in the bonding shop.

Figure 3-3: Bond Shop Process Sequence



One of the benefits of using an epoxy type adhesive to attach the body panels is that the adhesive can act as a liquid shim. All of the frames coming out of the frame shop are sure to have some dimensional variation to them. A limited amount of this variation can be compensated for by the epoxy. The bonding fixtures hold the panels in the proper location to ensure the completed car has good fit and finish.[8] The epoxy adhesive can fill small gaps between the panels and the frame. Of course there are limits to how much variation the process can handle. It is still vitally important the framing fixtures are designed to provide a very high level of dimensional accuracy.

3.4 General Assembly Process Detail

The general assembly (GA) process for this type of space frame vehicle is very similar to a typical BFI general assembly line. At the time that the vehicle enters GA, it looks very similar to a BFI vehicle. In both cases, GA receives a complete, finished appearance body with all of the body panels painted and installed.

The doors of the car have not yet been attached to the body as it enters GA. They remain off to provide easier access to the interior of the car and to reduce the chance for damage. The first time they are attached to the car is near the end of the final assembly line. In most auto plants today, the doors are attached to the car before the paint shop. This ensures that they are painted at the same time and have the same final appearance. GA is sometimes performed with the doors remaining on, however, in most cases the doors are then taken off again at the beginning of GA.

[8] Fit and finish refers to the final appearance of the product. A car that has good fit and finish has all of its parts located correctly and has consistent, properly sized gaps between panels.

The assembly process is finished and then they are re-installed at the end of the line. With the manufacturing process explored here, all of the exterior body panels already have their final color and appearance when arriving to the bond shop. Therefore, there is no reason to attach the doors to the car at that earlier stage. They can be built up separately in the bond shop, with all of the door and window hardware installed, and then sent directly to their point of use near the end of the assembly line.

In the GA area, most of the assembly tasks can be performed on a moving car and powered conveyance would be used to maintain a constant flow. Upon entering GA, the car is mounted on what is known as an overhead chain-on-edge conveyor. This conveyor is chain driven and uses carriers that hang from the overhead rail and then reach underneath the car and provide points for the car to rest on. The car starts off at a height low enough to provide easy access to the interior and engine compartment areas. It can then be raised up in height to provide easy access to the underside of the car. At that point, the engine, transmission, suspension, etc. can be more easily assembled to the car. After completing the higher elevation work, the car can be dropped back down in height and set onto a flattop conveyor. This flattop conveyor is built into the floor of the plant and operates like a moving sidewalk. On the flattop conveyor there is no need for any type of carrier or cradle, so workers would have full access to the car. It is at this point that the doors can be easily installed.

As mentioned earlier, the parts assembled in GA are very similar to the parts assembled in GA of a BFI car. One difference could be in a slightly reduced part count because of fewer interior trim pieces. If the interior body panels are textured composite panels, there is no need to cover them up with additional plastic trim pieces. They can provide the finished appearance.

The GA shop receives a few major subassemblies from suppliers outside of the plant. The rear suspension can be sub assembled so that it can be raised up and attached to the car as one single unit. The instrument panel inside the passenger compartment can also be sub assembled so that it can be installed into the car as one part. The engine arrives at the plant partially dressed.[9] This reduces amount of prep work each engine requires before being installed into a car. These types of subassembly strategies are consistent with what is commonly seen in the automotive industry today. It allows for more of a modular type build in the final vehicle assembly plant.

3.5 Chapter Summary

This chapter has described the manufacturing process for bent tube space frame vehicles. It explained the overall assembly plant process flow and then provided more process details for the frame shop, bond shop and general assembly area.

The next chapter explores some of the body panel alternatives for a space frame vehicle. It describes four options that were considered for this project, discusses their advantages and disadvantages and offers a cost estimate comparison. It then chooses the most viable of the alternatives.

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[9] Engine dressing refers to the process of attaching the required components, such as hoses and wires, to the engine before it is installed in the vehicle.

CHAPTER 4 – BODY PANEL MANUFACTURING

4.1 Body Panel Materials Considered

The purpose of this project is to stretch the boundaries of what we think of as low investment automobile programs. For that reason, some non-traditional panel materials and processes are considered. This type of space frame vehicle could be constructed using traditional steel body panels on both the interior and exterior. However, steel panels, even if low volume tooling is utilized, still require a significant investment.[10] The goal was to try avoiding or reducing this investment figure even further.

This project performed detailed analysis of four main panel strategy alternatives:

1. Open mold fiberglass, as used by the boat industry.
2. VEC® Technology – a closed mold fiberglass process from Genmar, Inc.[11]
3. A combination of composite technologies, including SMC, paint film and injection molding.[12]
4. A hybrid strategy using steel panels and VEC® Technology panels.

The chart shown in Figure 4-1 below illustrates why these four alternatives are investigated. The chart shows relative investment costs for the tooling to mold a set amount of parts in several composite processes. Assuming that the parts being molded are body panel type parts, it also estimates tooling cost for the equivalent steel stamping dies. This chart is not exact, does not include real numbers and would vary depending on the exact part being considered, but it does

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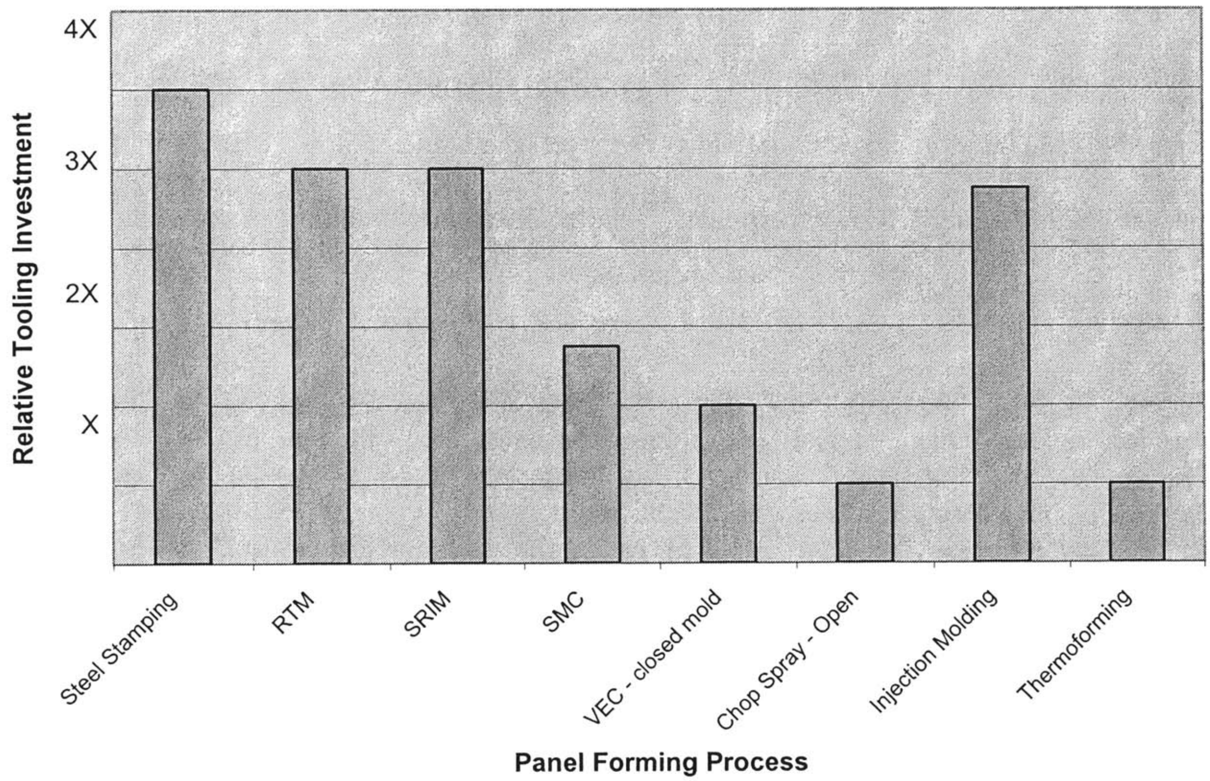
[10] Low volume tooling refers to the general category of tooling designs that decreases the required investment while typically making a sacrifice in cycle time.
[11] VEC = Virtual Engineered Composite
[12] SMC = Sheet Molding Compound

give an idea of the relative investment costs. When choosing which process to use for a particular part, many other design factors must be considered.

Figure 4-1: Body Panel Tooling Investment Comparison



As shown in this figure, the composite processes chosen for further investigation offer the potential for very significant investment reductions compared to steel panels. The four panel strategies that are considered will be detailed further in the next four sections. Section 4.6 will then compare the investment cost estimates for each panel strategy as well as the expected piece price for a complete set of body panels. The investment figures are assumed to be approximately equal between the U.S. and Mexico. However, the piece prices are adjusted to account for labor rate differences where appropriate.

4.2 Open Mold Fiberglass

The open mold, or hand lay-up, fiberglass process has been around for decades. It capitalizes on the tensile strength of glass fibers to provide reinforcement for a plastic resin. It has been used in the recreational boating industry since the 1950's and has changed little during that time. It is also used sparingly in the automotive industry for aftermarket parts, specialty products and for some tractor-trailer cabs. However, it has never been used extensively in mass-produced passenger cars. It has long cycle times and requires very inexpensive tooling so it lends itself to low volume applications.[13] While there are some limitations to the shape of parts that can be molded with open mold, a very wide range of sizes is possible.

The tools for open mold fiberglass parts are also made out of fiberglass themselves. A plug is made, typically out of wood, in the shape of the finished part's surface. This plug is then used to shape the fiberglass tools. Each tool has a relatively short life (1,500-2,500 parts) and a long cycle time (8 hours for a boat hull), so the plug can be used to create several tools in order to mold multiple parts at once or to replace spent tools.[14]

Because it is an open mold process, only one tool is required to mold each part. The mold lies horizontal and the material for the part is applied to the top surface. The first material applied to the mold is either a gel coat or primer spray. This gel coat or primer will end up being the exterior surface of the final part, so the final part's intended application will determine which material to use. If it needs to be painted later, a primer coat will be used. If it is for an application where a gel coat finish is desirable, there is no need for the primer. The appropriate

[13] Cycle time is the amount of time required to complete a process. It is the elapsed time in between the start and completion of a part.
[14] A tool that has reached the end of its usable life is referred to as a "spent" tool.

color gel coat can be applied directly to the mold. Gel coat finishes are typically used on all fiberglass boats as well as a few other fiberglass applications. The gel coat is colored to provide the desired final appearance of the part being made. A gel coat does not provide a surface finish exactly like a modern automotive paint job, but it does give a paint-like appearance. For this analysis, it is assumed that a primer coat is used because a traditional automotive paint job is required to meet North American automotive consumer expectations for appearance and performance.

After the primer coat is applied, a barrier coat of resin is applied to separate the gel coat from the glass fibers and prevent bleed through of the glass fibers.[15] After the barrier coat is in place, the glass fibers can be applied. The glass fibers are typically chopped into small pieces (on the scale of one inch) and mixed with resin before they are sprayed into the mold. Spraying on these chopped fibers results in random directional orientation so that the material has uniform strength and material properties in all directions.

Once the mold has been fully coated with the glass fibers and resin it is hand-rolled to ensure the fibers are lying flat and to remove air pockets. It then must be allowed to cure. Depending on the size and thickness of the part and whether or not curing ovens are used to provide heat, the part may require from one-half hour to eight hours before it can be removed from the mold. The part then must be pried loose from the mold and removed by hand. Excess material around the edges of the part is trimmed off to give the finished product.

[15] Bleed through is a condition where an inner material of a product works up to the surface and becomes exposed. In this case, bleed through would result in glass fibers working up to the surface of the panel and being exposed to the outside.

The open mold fiberglass parts can be molded with either a smooth surface or a textured surface. This process flexibility enables the use of open mold fiberglass for both interior as well as exterior body panels. For most exterior body panels, manufacturers want the smooth, shiny appearance that consumers are accustomed to. However, for interior panels, a textured finish is more appropriate for providing consumers with a comfortable, inviting passenger area. Molding these interior body panels with a textured composite can also be used to reduce the parts count for general assembly. Most cars today have steel inner body panels. This steel is then covered up in most areas with plastic trim pieces. If the body panels are textured plastic to begin with, most of these trim pieces can be eliminated.

As can be imagined from this brief process description, the open mold process is very labor intensive. It also has a very long cycle time. Curing ovens can be used to accelerate the drying process, but even with the use of ovens the cure time for automotive size panels would be much longer than the station cycle time on the vehicle assembly line. The panels would have to undergo some curing after the application of each material, with the longest cure time spent after the final application of the glass chop and resin. The total time through the panel molding process may be as long as 90 minutes. This would require that over 20 pieces of each panel part number might be required to be in process at any one time to keep up with the assembly line's production rate. This adds complexity and variation to the production system since each mold will not produce exactly duplicate parts.

The only parts of the open mold process that have been automated with much success are the spraying operations. Robots can be used to spray in the primer coat, barrier coat and resin/glass chop mixture, as they are in some personal watercraft manufacturing. Fanuc, a major industrial robotics manufacturer, produces a robot system designed specifically for this purpose. Fanuc's AccuChop® system is a process control package designed for automated fiberglass lay-up applications. This type of automation offers a couple of advantages over manual spraying. It significantly reduces the need to expose workers to the highest level of styrene emissions. It also improves the consistency of the final product. The robot will move at a constant rate as it passes the spray nozzle over the mold, resulting in a consistent material thickness.

However, this automation does not have a significant effect on throughput. The nozzles and spraying equipment itself limits the speed at which a panel can be sprayed. Therefore, each robot can only do the same amount of work as one person. Each robot also requires some preventive maintenance and a technician to keep it operating properly. For this project analysis, it was estimated that a bank of 28 robots would require 2 operators to perform cleanup and preventive maintenance between each shift. That same bank would also require the full attention of one trained technician to deal with ongoing programming and electrical problems.

Figure 4-2 shows the results of financial analysis that was performed to determine if automating these spray processes is a good idea. Appendix 3 shows the spreadsheets used to perform that financial analysis. Figure 4-2 shows the payback period and net present value for this type of automation project. The analysis was performed for both United States production as well as Mexico production. It is assumed that these fiberglass panels would be purchased from a local composite parts supplier, so labor rates for hand lay-up fiberglass operators in Michigan were used for the United States analysis. These labor rates were obtained from United States Bureau of Labor Statistics sources. Labor rates for Mexico production were obtained from a report published by the Mexican Bank for Foreign Trade. General manufacturing labor rates were used for this Mexico analysis. A more detailed spreadsheet from this analysis can be seen in Appendix 1.

Figure 4-2: Open Mold Automation Analysis

	United States	Mexico
Assumed Cost of a Robot	$70,000	$70,000
Labor Costs per Person	$44,067	$8,914
Headcount Reduction	-19%	-19%
Payback Period	0.7 yrs	6.9 yrs
NPV Effect on 5-yr Program	+ $32 Million	- $2.0 Million

As shown in the chart, the automation investment makes very good sense in the US labor market. The investment has a payback period of less than one year and positive net present value (NPV) when comparing the equipment costs to the labor savings. For Mexico production, the automation is not a good investment. The payback period is greater than seven years and it has a negative NPV impact on the project. The cost of capital used for this analysis was set to match GM's current return on investment (ROI) for their vehicle operations. Capital committed to this type of low investment manufacturing operation could have been invested in more traditional programs that are assumed to match the company's current ROI.

Another major drawback of this open mold process is the environmental implications it has. The spraying processes are very messy and give off high levels of styrene emissions. Because the part is open to the environment as it cures, it also continues to give off styrene as the resin dries. These styrene emissions cause health concerns for the workers that are exposed to them and are regulated by the Environmental Protection Agency when given off in large amounts. Workers involved in the spraying operations have to wear respirators and the emissions abatement equipment requires a large investment. If a plant were producing all of the panels for this type of low volume automotive application, the abatement equipment would cost in the tens of millions of dollars.

The piece price estimates for open mold body panels are adjusted for the labor rate difference between the U.S. and Mexico. The tooling investment cost is considered to be negligible, due to the short life of the fiberglass molds. Each tool only has a life of a 1500-2500 parts and there would be an ongoing process of replacing the molds. Therefore, the tooling cost is considered a variable cost and is rolled into the piece price estimates.

4.3 VEC® Technology

VEC® Technology is a process owned by Genmar Holdings, Inc of Minneapolis, MN. Genmar is the world's largest producer of recreational boats. They have been using the VEC® process for the last few years to produce many of their boat hulls and decks, as well as some smaller parts. It produces a material that is very similar to the traditional open mold boat manufacturing, but it is a more consistent, higher-quality final product.

The VEC® process is a closed mold fiberglass process. The molds themselves are also made with fiberglass skins. There is both a top and bottom mold skin, which provide the new part with its shape. These mold skins are sealed over the top of steel pressure vessels, which are then filled with water. Because the water in the pressure vessels is incompressible, it helps the mold skins maintain their shape and prevents them from collapsing when material is injected into the mold.

Before the mold is closed, a gel coat or primer is sprayed onto the mold skin that shapes the outer surface. Glass fiber mats are then laid into the bottom mold. These glass fiber mats help provide the final product with its strength and serve the same purpose as the chopped glass fibers in the open mold process. They are laid in critical areas within the part geometry. After the glass fiber is in place, the mold is closed and resin is injected under pressure. The mold is heated and allowed to set for a specified length of time as the resin cures. The mold remains closed during the injection and curing processes. Therefore, the VEC® process does not have the same concerns with styrene emissions that the open mold process does. Styrene in the material is trapped within the mold and cannot escape into the environment. The workers do not require special equipment and the plant does not have large amounts of styrene emissions to deal with.

The closed molds in the VEC® process utilize many sensors and controls to regulate the pressure and the temperature of the water in the pressure vessels. This water is heated to apply heat to the curing part. As the resin is injected, it is also continuously monitored. The formulation of the resin mixture is adjusted slightly throughout the injection process to control how quickly it sets up and starts solidifying. Control of all of these parameters enables acceleration of the molding process. A part that requires eight hours in the open mold process may only require thirty or forty-five minutes in the VEC® process. This molded part then must be trimmed up similar to the open mold process parts to produce the final product.

As with the open mold process, the VEC® process can be used to produce parts with a smooth finish as well as parts with a textured finish. Again, this can be taken advantage of by reducing the number of interior trip pieces that are needed because there are no steel inner panels to cover up.

The VEC® process does enable multi-cavity tools, so multiple parts could be molded at once in each VEC® cell. The basic VEC® cells were designed to mold hulls for recreational boats, which are typically up to about twenty feet in length and seven feet in width. In that same area, each VEC® cell could produce five different parts for a car if the parts are matched up correctly. Therefore, if a car were designed to require thirty molded parts, six different tools would be necessary. Because of throughput issues, production would also require several copies of each tool to be used. If the plant was running at the low volume limit of 50,000 units, 14.6 jobs per hour, and each VEC® cell can only produce a set of parts every half hour, 8 sets of each mold would have to be in use to provide the necessary volume of parts. This is far fewer than is required for the open mold process and requires less than half of the floor space at the panel supplier.

The VEC® process does greatly reduce the labor content as compared to the open mold process. However, because of the slow cycle times, labor does remain a significant percentage of the total cost. Teams of three workers can only produce, depending on part size, a few parts per hour operating a VEC cell. Therefore, piece price estimates were adjusted for the labor rate differences between the U.S. and Mexico. Similar to the open mold process, the fiberglass

VEC® tools also have a short life span and the tooling costs are considered part of the variable cost that is rolled into the piece price.

4.4 Composite Technologies Combination

Most passenger cars manufactured today are primarily steel, but a few composite technologies are used a fair amount and have gained greater acceptance in recent years. A combination of these composite technologies could be used to complete construction of a low investment space frame vehicle where the underlying steel tubes provide the vehicle with its strength and rigidity.

Paint film technology is something that has been used a fair amount in automotive applications, but mostly for limited types of parts. Front fascias and rocker panels are two of the most common paint film applications. These parts have to hold a particular shape, but they are not relied upon for any structural strength.

Paint film is created by a process that paints a very thin layer (~1 mm) of plastic film with traditional automotive paint materials. Paint films can be created in any automotive paints, using flat colors, metallic colors, tri-coats, clear coats, etc. This paint film can then be cut and applied to parts using a variety of different processes. The process considered for use here is known as thick film thermoforming.

In thick film thermoforming, the paint film is backed with an approximately 4 mm layer of PPO plastic resin.[16] The PPO plastic and paint film combination can then be thermoformed into the desired shape. The plastic backing provides enough strength for the part to maintain its designed

[16] PPO = Polyphenylene Oxide.

shape, but it cannot be relied upon for structural rigidity. This type of thick film thermoformed part cannot typically be used for structural panels, such as the floor, or for parts that experience high heat loading, such as the hood. For a space frame vehicle, it could be used to manufacture all of the vertical external panels. For example, the door outer panels could be created using thick film thermoforming because the steel tube frame would provide all of the necessary structure and strength.

SMC, sheet-molding compound, is a process that has been used for several years to produce automotive body panels. Within GM, it is used to produce several of the body panels for the Corvette. SMC is similar to open mold and VEC® parts, in that they utilize chopped glass fibers to provide reinforcement strength. The fibers are deposited in between two layers of a resin paste and the resulting sheet is then pressed between rollers. The product is gathered into rolls and stored until it has undergone a maturation period and reached the desired molding viscosity. The sheet is then used on a later date (within 1 month) to be compression molded into the desired shape.

One of the benefits of the SMC process is that it produces high strength parts that can be used in applications where the part must provide significant structure. SMC is also capable of withstanding high heat loading. These characteristics help make SMC panels very suitable for horizontal body panels such as the hood. The strength also enables its use for the floor pan, dash board, wheel arches and bumper beams. The tooling investment for an SMC part is typically lower than an equivalent steel part by 25% to 50%, depending on the part design and desired quantities, but that tooling investment is still higher than is required for thick film thermoforming parts. For that reason, the strategy taken in this analysis is to minimize the number of SMC parts used. SMC is only used for parts that specifically require the properties and performance that it provides.

Using this composite combination strategy, the interior body panels would be manufactured using typical injection molding. As with the thick film thermoformed parts, the interior panels would not be required to provide structure or strength because they would be mounted to the underlying steel frame. They could be molded with the typical colors and textures that consumers are accustomed to seeing on the interior of vehicles and would provide the strength and durability to hold up to the conditions they experience there. These interior body panels would serve two main functions. They would provide closure between the frame members and the interior of the car as well as provide the finished appearance for the interior.

With this composite combination, the only body panel that would require painting would be the hood, which is made from SMC. The other SMC parts, are all on the bottom of the car or hidden by other panels. Therefore, there is no reason for them to be painted. Because the hood is the only part that would need painted, this eliminates the need to invest in enough paint shop capacity to run the full vehicle production through. If this type of vehicle were executed at a brown field site that already had paint facilities, the hoods could be run through the existing paint shop. If this vehicle were executed at a Greenfield site, bringing the hoods in from the supplier having already been painted could eliminate paint shop investment.

One concern with this type of composite combination is getting an exact appearance match between the different materials. The painted hood would be finished at a different time and place than the paint film for the rest of the exterior body panels. This could make it very difficult, if not impossible, to get an exact color match. Even if the colors are matched very closely according to all of the standard paint finish metrics, they may not have the exact same appearance to a customer because they are different materials. This makes appearance match especially difficult with large surface area panels that are side by side.

4.5 Steel and Composite Hybrid

North American vehicle owners are accustomed to the appearance and performance of steel body panels on their cars. Steel stamping processes have been developed over the years so that they produce consistent, high quality surface finishes. Paint processes have also been fine tuned over the years to work well with these steel surfaces to provide the jewel effect of a smooth, glossy, high quality exterior appearance. Composite processes have progressed over the years and continue to progress. However, in the low investment range of composite processes, there is still some risk in being able to consistently produce a high quality, smooth finish that can match steel panels in a mass production environment.

The fourth main body panel strategy considered is one that uses steel body panels for the exterior in conjunction with composite body panels for the inners. The steel outers would provide the exterior appearance that people are accustomed to while the composite inners would help maintain a lower investment level. The composite process chosen for these inners is the VEC® process discussed earlier. The VEC® process requires a lower tooling investment than SMC or injection molding, provides higher strength parts than the thermoforming and is more viable for North American automotive mass production than the open mold fiberglass process.

The outer steel panels would be mounted directly to the steel tubes of the space frame, similar to the composite panel strategies. Mounting techniques would have to be adapted to fit the exact design of the car, but in most cases it would be desirable to bond the panels to the frame with adhesive. Some development work may be required to fine-tune this adhesive bonding process to ensure a reliable adhesion to the autophoretic® coating of the frame. Adhesive bonding should provide a quicker, easier manufacturing process than mechanical fasteners. However, mechanical fasteners could provide more ability to finesse the panels into a good fit if necessary. That mounting issue would have to be decided after a detailed vehicle design was completed and some comprehensive testing could be performed to determine the dimensional capability of this bent tube space frame architecture.

With this hybrid strategy, all of the steel outer panels would require traditional painting. The frame would not be painted because it is protected with the autophoretic® coating. The VEC® inner body panels would not be painted because they would be molded with a textured gel coat that provides the desired appearance for the finished interior. So the outer steel body panels would be painted separately, before being bonded to the frame.

All of the outer panels for a complete car would be mounted on to a paint buck and run through the paint shop. This paint buck is a fixture that holds each of the panels and then travels on the conveyor system through the paint shop. It has been used in other applications where the complete car is not painted as a whole, but instead the body panels are painted before being attached to the car.

As with the composite combination strategy from section 4.4, there is very low labor content in the cost of steel panels. Therefore, the piece price for the outer steel panels was assumed to be approximately equal in both the U.S. and Mexico. The VEC® parts have more labor content built into their piece price. For that reason, the VEC body panel costs are adjusted for the labor rate difference between the U.S. and Mexico.

4.6 Cost Comparison and Conclusions

Each of the four body panel strategies that have been explored were chosen because of their potentially low investment. They all offer a significant reduction from using a traditional stamped steel BFI architecture. Figure 4-3 below shows the expected levels of investment for each option as well as the expected piece price per complete set of body panels. The investment costs include only the tooling required to form the body panels and do not include paint shop costs, which are assumed to be the same for all four options. The numbers have been adjusted and disguised to protect confidential cost information, but the conclusions drawn are still the same. For the body panel tooling investment, the lowest investment figure is designated as X. The other investment figures are shown as approximate multiples of that X value. Similarly, the lowest panel piece price per car is designated as Y. The other panel piece price figures are shown as approximate multiples of that Y value.

Figure 4-3: Body Panel Technology Cost Comparison

Body Panel Technology	Body Panel Forming Investment	US Panel Piece Price per Car	Mexico Panel Piece Price per Car
Open Mold Fiberglass	2.5X	2.30Y	3.00Y
VEC® Closed Mold Fiberglass	-	1.75Y	1.50Y
SMC/Paint Film/ Inj. Mold Combo	X	1.25Y	1.25Y
Steel Outers/VEC® Inners Hybrid	**1.5X**	**1.15Y**	**Y**

The panel forming investment figure for the open mold fiberglass only covers the emissions abatement equipment that would be needed to control the styrene emissions. As mentioned in section 4.2, the tooling for the open mold process is considered a variable cost and is rolled into the piece price per car. The same is also true for the VEC® closed mold fiberglass investment figure. In that case, the extensive emissions abatement equipment is not needed and the tooling cost is still rolled into the piece price per car.

Of the options considered, the optimal panel strategy chosen for a North American implementation of a bent tube space frame vehicle is the hybrid strategy, using steel outer panels and VEC® composite inner panels. This strategy does require an investment that is approximately 50% larger than the SMC / paint film / injection molding combination, but it offers a lower piece price per car as well as a couple of very significant benefits. The steel outer panels of the hybrid strategy provide a surface finish that consumers are accustomed to. It can give the finished car the jewel effect of a high quality exterior appearance. The steel hybrid strategy also avoids the problem of trying to match appearances of different panel materials. All of the exterior panels would be steel, whereas with the combination strategy, there would be both paint film parts and SMC parts on the exterior. The steel outers will also provide more strength than the thick film thermoformed paint film parts.

Based upon the estimates developed for this project, the open mold fiberglass process requires too much labor to be cost competitive in either the US or Mexico labor markets. Even with the automation analysis that was shown in section 4.2, there is still too much labor content. It also requires a larger investment due to the emissions abatement equipment.

Using the VEC® process for all of the body panels does help eliminate the styrene emissions concern of the open mold process, but the long cycle times still require too much labor content and do not appear to be cost competitive by the estimates developed during this project. It is important to note that these cost estimates were developed for this project with limited data from Genmar sources. They were not developed through any formal quotation process working directly with Genmar.

The hybrid strategy uses the VEC® closed mold process for all of the inner body panels. One of the results of this combination is that it balances the high investment and low piece price of the steel outer panels with the low investment and higher piece prices of the VEC® inner panels. This is the ideal choice in both the Mexico production scenario and the US production scenario. Due to the labor difference, the VEC® cost estimates are lower in Mexico and it is expected that the panel piece price would be 15% higher in the US, while the investment would be approximately equal.

4.7 Chapter Summary

This chapter identified four body panel strategies that were considered for this project. It described the processing of each panel type and explored the advantages and disadvantages of each. It then provided a comparison of the investment and piece price required for each of the options and chose the most viable one for North American use.

The next chapter highlights the conclusions about using a bent tube space frame architecture in North America, followed by some conclusions for using a bent tube space frame architecture in other parts of the world. It then touches on the effects of the architecture choice when defining a new vehicle program. This is followed by discussion of a global low investment strategy and some of the hurdles for low volume, low investment vehicle manufacturing. Then the results of this project and its impact on GM are discussed.

CHAPTER 5 – LOW INVESTMENT STRATEGY CONCLUSIONS

5.1 Conclusions on Bent Tube Space Frame Construction in North America

Earlier sections of this thesis detail some of the analysis involved in determining the optimal manufacturing strategy for bent tube space frame vehicles in North America. As detailed in those sections, the frame is constructed using rectangular steel tubing, cut and bent to the shapes required to weld into a space frame structure. This space frame would then be covered with VEC® composite inner body panels and stamped steel outer body panels. Of the options considered for this project, this option provides the best combination of investment, piece price, manufacturability, performance and quality. However, this is not a better option for the North American market than the traditional steel BFI architecture because the labor costs are too high.

Figure 5-1 below shows a comparison of this bent tube space frame construction versus a more traditional BFI construction for a small family sedan. The estimates for both architectures are based on the assumption that production is in the low volume range under 50,000 units per year. The steel BFI cost figures are taken as the baselines. For assembly plant investment, the steel BFI plant investment is assigned a value of A. The bent tube space frame assembly plants are assigned a value as a percentage of that baseline A. For both Mexico production as well as US production, the bent tube space frame plant investment is estimated to be 56% of the steel BFI plant. The same approach is used for labor costs per vehicle, with the steel BFI baseline assigned a value of B. The labor costs per vehicle for a bent tube space frame relative to a steel BFI produced in the US are estimated to be 17% in Mexico and 173% in the US.

Figure 5-1: Total Plant Investment and Labor Costs

	Bent Tube Space Frame in Mexico	Bent Tube Space Frame in US	Steel BFI in Mexico	Steel BFI in US
Assembly Plant Investment	0.56*A	0.56*A	A	A
Body Panel Tooling Invest.	0.25*B	0.25*B	B	B
Panel Piece Price per Vehicle	1.32*C	1.52*C	C	C
Plant Labor Costs per Vehicle	0.17*D	1.73*D	0.10*D	D
Total for 5-yr Program Life	0.76*E	1.40*E	0.67*E	E

As shown by these results, the bent tube space frame architecture requires 73% more assembly plant labor content than an equivalent BFI vehicle. The higher labor costs are also present in the body panel piece price per vehicle for the low investment composite panel technology. The labor costs for bent tube space frame production in Mexico is only 17% of the labor costs for BFI construction in the US, but it is still significantly more than the labor costs for BFI construction in Mexico. For low investment programs, this bent tube space frame construction in Mexico is the most viable option. The panel piece price and labor cost per vehicle both rise compared to steel BFI construction in Mexico, as does the total plant/labor/body panel cost for a five year program, but the required up front investment is cut nearly in half.

US production of a pure bent tube space frame does not appear to be a viable option. The labor costs are too high to make it a reasonable alternative in the low volume mass production of a family sedan. It may be acceptable for an extremely low volume product or a specialty vehicle that can afford to charge a premium, but not a car aimed at basic family use.

There are examples of space frame type vehicles currently being mass-produced in the US and other expensive labor market countries in Europe. The Corvette is one prevalent US example of that. GM has been manufacturing the current design of the Corvette successfully in Bowling Green, Kentucky for several years now. As described in Chapter 2, the Corvette has some design elements from both BFI and BOF architectures, but it is also uses a lot of the principles of a space frame architecture. The key element that makes it much more attractive for US production than the pure bent tube space frame construction considered here is its use of hydroforming. The hydroforming process enables the design and manufacturing of more complex frame members. These parts can be designed with locating and orienting features built in, which reduces the amount of frame shop fixtures required. An area of the frame that may have required a dozen parts using only bent tubes may now also be able to be manufactured using only a few parts. The use of hydroformed frame components could reduce the parts count to one-third of what is required for a pure bent tube space frame. This reduced parts count also means reduced welding and reduced labor in the assembly plant.

Hydroforming does require the use of steel dies which require a significant tooling investment at the beginning of a new vehicle program. This will prevent a vehicle that uses hydroforming from matching the overall investment cost that a pure bent tube space frame vehicle can achieve, but the resulting reduction in variable costs and piece price can be used to make the overall vehicle program more profitable. If some of the other low investment principles are maintained and a low investment panel strategy is used, it is expected that the investment could still be kept below the traditional investment level of a steel BFI vehicle. It is the author's belief that the use of technologies such as hydroforming is required for making a profitable space frame vehicle with US production. Detailed analysis on this subject is outside the scope of this project and is left for further study.

It is important to keep in mind that the strategy developed in this thesis has been enabled by the use of VEC® composite panels for over half of the body panels on the space frame vehicle. While this VEC® process appears to produce parts acceptable for use as interior panels in this type of automotive project, it has not been proven in practice. There is some risk involved in applying this relatively new technology to this type of application. There is also some risk in development of the bonding process. There has not yet been a production example of bonding both steel body panels and VEC® composite panels to steel tubes that have undergone autophoretic® coating.

5.2 Global Strategies with Bent Tube Space Frame Construction

Moving labor to Mexico does offer a cost advantage that is approximately an order of magnitude difference as compared to the United States. There are also other global markets that offer even greater labor savings. With increasing automotive production in developing Far East countries such as Vietnam, China and Thailand, there are economies that are even more suited to this type of high labor content production. Similar environments can be found in developing areas of Africa. Labor costs in some of these countries are another order of magnitude lower than Mexico labor costs. Every $1,000 worth of labor in the US may only cost approximately $100 in Mexico and only $10 in a country like Vietnam. At labor rates in this range, the total five-year cost as computed above is lower for a bent tube space frame vehicle than it is for a steel BFI vehicle.

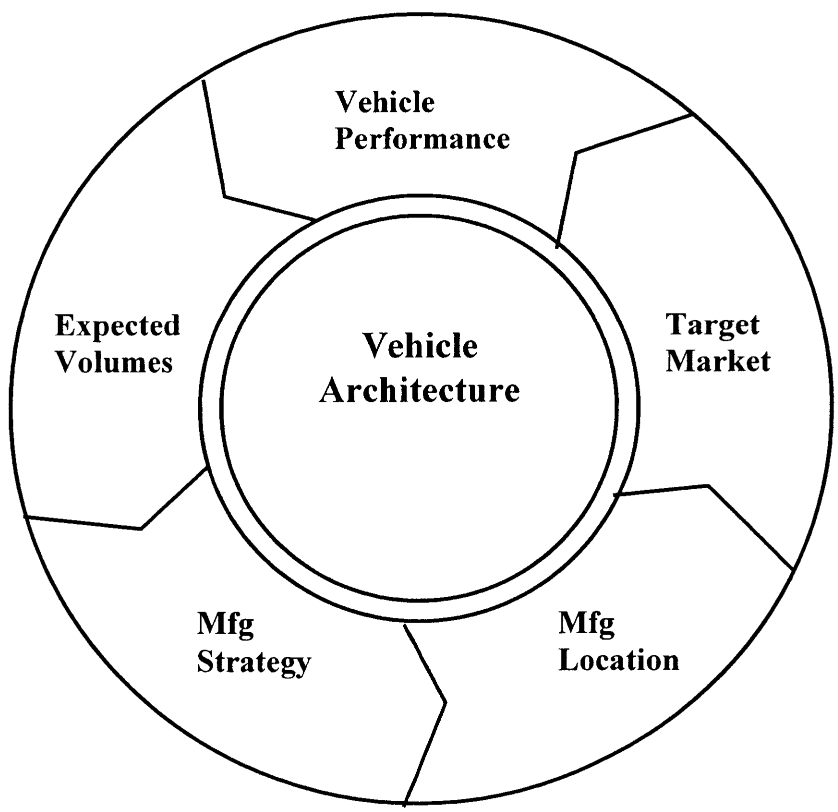
This type of bent tube space frame vehicle may also be more appropriate for developing countries with low labor rates and emerging automotive markets. The reduced investment for this type of program minimizes the amount of risk a manufacturer must accept when entering a new market. The bent tube space frame design can also be used to speed up the product development process. As mentioned earlier, the elimination of stamping dies from the parts that provide the vehicle's structure and strength enables quicker, cheaper prototype build iterations during the development process. This allows a new product to be brought to market more quickly in one of these developing markets.

5.3 Deciding on a Vehicle Architecture

As described in Chapter 2, there are three main types of vehicle architectures used in automotive manufacturing. There are also a large number of variations on these three basic architecture types that combine elements from two or all three varieties. Each of these different architectures then requires a different manufacturing process and has different costs associated with it. There are also performance differences for each architecture type when used in different styles and shapes of vehicles.

As depicted in Figure 5-2, the vehicle architecture becomes a central element of the entire vehicle program. Each vehicle concept starts off with a target market in mind. The vehicle design concept and target market can then be used to set vehicle performance requirements. Based on the vehicle performance, resulting target price and target market, expected sales volumes can be estimated. The expected production volumes drive the vehicle program towards a certain manufacturing strategy. The manufacturing strategy includes the manufacturing locations, which has to take into account the target market. All of these elements also influence and are influenced by the architecture chosen. A traditional BOF architecture may be most appropriate for a high volume product that requires a lot of strength and rigidity, such as trucks. A traditional BFI architecture may be most appropriate for a high volume product that does not require as much strength but may require a lighter structure for good fuel economy. As detailed in this project, some variation of a space frame vehicle may be most appropriate for a low volume product where maintaining a low investment figure is critical.

Figure 5-2: Importance of Architecture Choice



The importance of the architecture selection to the overall vehicle program cannot be overstated. The architecture choice influences and is influenced by many of the other key parameters that define a vehicle program. If the program is defined as a certain type of vehicle, with certain performance criteria and certain expected volumes, it will lead to the selection of a specific architecture design. However, if any of those program details changes, which they often do, it may result in the original architecture choice to be inappropriate. If or instance, the expected volumes change, this could have significant impact on the types of manufacturing processes that will be used and which type of architecture should be used. It is important that a new vehicle program begins with a very clear definition of what the vehicle needs to be and what the expected production volumes are. If these parameters of the vehicle program change very early in the program life, the development team needs to take a serious look at whether it makes sense to continue with the chosen architecture or if the vehicle design needs to be started over.

5.4 Global Low Investment Strategy Conclusions

As detailed in Section 5.2, a pure bent tube space frame architecture can be considered for production in developing markets with low labor costs. In the Mexico labor market, it is viable and greatly reduces the manufacturing investment, but after five years, the higher labor costs result in the total program manufacturing costs being approximately equal to the total program manufacturing costs of a steel BFI vehicle. Bent tube space frames are clearly not the way to achieve low volume, low investment programs in the United States. In the US labor market, other manufacturing processes have to be used to reduce the labor content of the vehicle.

What does this mean for a global low investment manufacturing strategy for GM? It appears that it would be a financially attractive option to manufacture bent tube space frame vehicles in developing countries for sale in the United States. However, this is a very unlikely option anytime in the near future. Most workers at GM's manufacturing facilities are members of the United Auto Workers union. The UAW has a lot of power in the union / corporation relationship and they would be unlikely to allow a significant portion of GM's sales to be imported from other countries. If it became prevalent enough, the US government may also step in to limit imported production in order to ensure jobs remain within the country. In the past, the government has threatened import restrictions on foreign brands such as Toyota and Honda. In order to defend against any such restrictions, these foreign companies have built more and more production capacity inside the US to spur their market share growth. For these reasons, extensive use of these manufacturing processes in developing countries would probably have to be targeted for vehicles sold in those same regions. In those developing markets, the body panel strategy could be modified to meet the expectations and needs of the market. Consumers may be looking for an affordable car and not have the same quality and appearance expectations that US consumers have. In that case, cheaper composite body panel processes could be used to match the product to the market.

GM also has an issue with fixed labor costs for the near future. Contractual agreements with the UAW prevent GM from getting rid of employees. Even if they are laid off from a plant, the employees go into a labor pool for future reactivation and GM continues to pay them. Due to increased productivity at their plants, GM has a surplus of labor most of the time. If this surplus of labor is expected to continue for several years, it may make sense to consider some of the highly manual, low investment manufacturing techniques for use in a US program. If these employees are going to be paid anyway, it is better to be getting some labor from them at the time.

Another possible application for this highly manual bent tube space frame construction could be with specialty or niche vehicles in the North American market. Programs such as GM's halo vehicles could be a viable option. A vehicle like the SSR is a low volume, unique product that may be able to charge a premium due to its limited production. A premium product like this is more likely to be able to afford the increased labor costs. At the same time, radical designs such as the SSR are never guaranteed to meet sales expectations. Radical designs may excite a large number of consumers and greatly exceed expectations or they may miss their target market and fall well short. Low investment programs using highly manual processes could be used to help reduce the risk of those programs. If sales forecasts are not met, the sunk cost in the program investment is not as great.

5.5 Low Investment / Low Volume Enablers and Hurdles

The shift in automotive manufacturing towards low volume and low investment programs requires some major shifts in traditional thinking. It requires the use of processes and techniques that previously would not have been considered for vehicle production and may require the abandonment of traditional processes that have been accepted as a standard part of every new program. Some of the composite technologies considered for this project are not typically considered an option for extensive use in automotive mass production. To accelerate the progress towards low investment programs, more of these types of technologies need to be considered. Processes such as the VEC® technology may require more development work before they are acceptable for automotive use, but that development work could be the key to unlocking further low investment breakthroughs.

Manufacturing engineers in the automotive industry also need to rethink some of the processes that are accepted standard in vehicle manufacturing. As discussed during some of the process details earlier in this thesis, increased automation is not always a good thing. In particular, heavy-duty conveyance systems are very expensive investments for automotive plants. Those large investments are not necessary in many parts of low volume environments. During the stages of the production process where the vehicle remains stationary while being worked on, such as in the frame shop and bond shop detailed in Chapter 3, it can be just as effective to have the product conveyed manually from station to station. Powered conveyance adds a large investment cost while providing only marginal productivity gains on slow moving lines. Similarly, welding processes in automotive plants are typically automated. As described in the frame shop details for this thesis, a bent tube space frame vehicle would use manual MIG welding to achieve low investment goals.

Another hurdle for implementing this type of low investment program is with the organizational and labor issues that accompany the switch to a radically different production system and environment. Some of the highly manual processes detailed in this thesis would require more skilled workers than the highly automated processes used in most current automotive plants. Each vehicle would require more craftsmanship to construct a high-quality product. Workers on the line will have to take more responsibility for the quality of the final product and will have to be given enough empowerment to feel comfortable with the increased responsibility. This reliance on a higher level of craftsmanship would also increase the importance and complexity of quality control processes. Manual processing will not typically provide the same consistency that workers are used to seeing from automated processes.

As mentioned earlier, some of the enablers for low investment automotive manufacturing may be increased use of composite technologies that have not traditionally been used. Automotive manufacturers and suppliers are constantly working to further develop these composite technologies for increased use on new vehicle programs. There is also continued work to develop low investment techniques for steel and aluminum forming for low volume body panels. Breakthroughs in these technologies will help enable low volume, low investment vehicle programs.

One of the other low investment enablers is more disciplined use of existing principles. Parts reuse is a concept that has long been used at GM as well as other vehicle manufacturers. Parts reuse is the act of designing a new car so that it utilizes existing components from existing vehicle models wherever possible. If a component has been manufactured for a different model, then the design and tooling is already available. There is no reason to design a very similar part that will require a separate set of tooling and more development time. One of the keys to parts reuse is to maintain discipline while practicing it. It is common for parts that are intended to be reused to end up being modified slightly, or “tweaked.” This tweaking may seem safe and inexpensive, but it then requires more validation testing. This validation testing then may contribute to extending the development process and opens the testing up to more failures. Any testing failures then require further redesign and testing which adds to the overall development cost of the program. It is important that if a new part has to be constructed, it is designed to ensure that as many other existing parts as possible can be used with it. Product development leaders need to stress disciplined parts reuse while being careful not to sacrifice vehicle performance.

5.6 Results of Project and Action Taken Within General Motors

The internship project that this thesis is based upon was successfully completed during the time spent at GM's Technical Center. The conclusions detailed above about the viability of bent tube space frame construction of vehicles in North America were presented to several audiences.

Details and results of this project were presented to the GM Vice President of Vehicle Operations and GM Group Vice President of Product Development. Presentations were also held with multiple vehicle program teams within GM North America. Discussions were held between these program teams and the author of this thesis during the program team's decision process about how their vehicle should be designed and manufactured. The goal of these presentations was to educate the audiences about the findings of this project and related projects. It provides the participants with background into some of the novel low investment manufacturing techniques considered here. This is intended to spur more creative thinking about how vehicle architectures can be designed to reduce manufacturing investment and total program spending. It opens up the minds of the program teams and executives to a wider variety of possibilities for designing and building cars.

This project focuses on a small part of developing a corporate strategy for low investment, low volume manufacturing. It maintained an emphasis on a pure bent tube space frame and four different body panel strategies, which use a small group of selected composite processes. It reveals possibilities for further study to develop new manufacturing processes and strategies. The results have shown that for North America production, extensive use of hydroforming in the space frame needs to be studied further. There are other metal forming techniques that could also be included in a more comprehensive study. It is important that novel manufacturing processes are not disregarded before giving serious consideration to how they could possibly be used in future automotive manufacturing.

5.7 Chapter Summary

This Chapter wraps up some of the general conclusions about bent tube space frame construction and explores low investment, low volume manufacturing more generally. Some of the conclusions drawn are:

- Bent tube space frame construction in the US for a mass market family sedan does not appear to be viable due to the high labor costs in the vehicle assembly plant as well as the body panel forming processes.
- Bent tube space frame construction in Mexico can be a viable alternative to traditional stamped BFI architectures. The labor market costs result in the total program manufacturing costs being similar to the total manufacturing costs for a stamped BFI.
- Developing countries are the most attractive application of bent tube space frame construction. Their labor costs approach one percent of the labor costs for equivalent

work in the US. This low cost along with the need for fast to market products, provide a good fit for bent tube space frame vehicles.

- The basic vehicle architecture for a new program is a critical decision. It is tightly linked with the vehicles desired performance, expected volumes, manufacturing location and other parameters. A change in the vehicle program definition could affect which type of architecture should be used.
- Low volume, low investment manufacturing requires that engineers open up their minds and think creatively. Concepts never before used in automotive manufacturing may turn out to be key enablers, while at the same time, concepts that have been accepted as standard in automotive manufacturing may not be appropriate for low volume, low investment programs.
- To understand all of the costs and benefits of using space frame architectures, more of a full systems approach covering all stages of product design and development is needed. Through this study, potential benefits have been identified outside the manufacturing costs, but the study did not include the resources or time to accurately quantify all of those amounts.

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APPENDICES

Appendix 1: 2001 North American Production of GM Vehicle Models

(taken from The Harbour Report North America 2002)

GM Model	2001 Production	GM Model	2001 Production
Hummer H1	644	Chevy Tracker	55,021
Cadillac CTS	1,424	Buick Rendezvous	55,937
Cadillac Escalade EXT	3,071	Chevy Joy/Swing	58,853
Saturn Vue	3,284	Chevy Astro	59,585
Chevy Metro	5,950	Chevy Monte Carlo	65,293
Chevy CT (med. duty truck)	7,338	GMC Envoy	69,258
GMC Jimmy	7,640	Pontiac Montana	75,625
Cadillac Eldorado	8,171	GMC Yukon XL	81,216
GMC CT (med. duty truck)	12,350	GMC Yukon	82,458
Chevy Lumina	17,147	Chevy Avalanche	91,914
Pontiac Aztek	17,217	Cadillac Fleetwood Deville	98,420
Chevy Monza	17,804	Chevy Express	100,566
Oldsmobile Aurora	19,420	Saturn LS	103,516
Pontiac Firebird	20,281	Pontiac Sunfire	108,760
GMC Safari	22,679	Chevy Blazer	113,158
Cadillac Seville	25,421	Pontiac Venture	115,330
Oldsmobile Bravada	25,561	OldsmobileAlero	119,752
Chevy Camaro	27,108	Pontiac Grand Prix	131,105
Buick Park Ave	29,931	Buick Lesabre	135,338
Chevrolet Corvette	35,535	Chevy S10	141,644
Oldsmobile Silhouette	35,902	Chevy Suburban	154,726
Cadillac Escalade	36,657	Chevy Trailblazer	163,253
GMC Savanna	37,334	Chevy Malibu	169,967
Oldsmobile Intrigue	38,504	Saturn S	171,909
GMC Sonoma	39,379	Buick Regal	190,710
Pontiac Bonneville	46,795	Pontiac Grand Am	197,123
		Chevy Tahoe	199,365
		Chevy Impala	200,761
		GMC Sierra	220,268
		Chevy Cavalier	274,488
		Chevy Silverado	710,096

Appendix 2: Body Panel Parts Included in Analysis for this Project

Exterior Body Panels

1. Hood Assembly
2. Door Front Right, Outer
3. Door Front Left, Outer
4. Door Rear Right, Outer
5. Door Rear Left, Outer
6. Liftgate Outer
7. Bodyside Left, Outer
8. Bodyside Right, Outer
9. Roof
10. Bumper Rear
11. Bumper Front
12. Rocker Panel Right
13. Rocker Panel Left
14. Fender Right
15. Fender Left
16. Liftgate Sill Outer
17. Plenum

Interior Body Panels

18. Door Front Right, Inner
19. Door Front Left, Inner
20. Door Rear Right, Inner
21. Door Rear Left, Inner
22. Liftgate Inner
23. Bodyside Left, Inner
24. Bodyside Right, Inner
25. Bulkhead (dashboard)
26. Wheel Arch Right
27. Wheel Arch Left
28. Floor Pan
29. Rear Pan
30. Spare Tire Cover
31. Fuel Neck

Appendix 2: Open Mold Automation Analysis Spreadsheet

Automation Trade-off Analysis for Open Mold Fiberglass

Looking at robotic spraying versus manual spraying

United States

Annual Volume	50000
Hours per day/shift	7.3
Shifts per day	2
Days per year	235
Hours per year	3431
NWR	14.57

Cost of a robot	$ 70,000
man-year costs	$ 44,067

# of panels per car	32
# of panels per hour	466.34

LABOR COSTS

Fiberglass hourly wage in MI	$ 15.42
Hourly cost of benefits	$ 5.76
Total hourly labor costs	$ 21.19
Total man-year labor costs	$ 44,067

Labor cost breakdown		
72.8%	wages	
27.2%	benefits	
0.374	ratio of benefits/wages	

$ 14.26 hourly wage in 2000
$ 15.42 hourly wage in 2002*
*based on 4% annual increase

Assumptions:

1. Central/Western Michigan location
2. Supplier - non-union workforce
3. Robots require 1 person per 14 robots for nightly clean-up/PM
4. 3.5 minute process time for all spray operations
5. Robots require 1 person per 14 robots as Technician
6. Cost of capital is equal to 2002 GMVO return on assets*

GEL COAT

spray time per mold	3.5
# of molds per robot	17.14
fractional # of robots	27.20
whole # of robots	28
added investment	$ 1,960,000

Direct headcount w/o robots	36
Direct headcount w/ robots	4
headcount reduction	32
annual labor savings (2 shifts)	$ 2,820,318

BARRIER COAT

spray time per mold	3.5
# of molds per robot	17.14
fractional # of robots	27.20
whole # of robots	28
added investment	$ 1,960,000

Direct headcount w/o robots	36
Direct headcount w/ robots	4
headcount reduction	32
annual labor savings (2 shifts)	$ 2,820,318

GLASS CHOP

spray time per mold	3.5
# of molds per robot	17.14
fractional # of robots	27.20
whole # of robots	28
added investment	$ 1,960,000

Direct headcount w/o robots	36
Direct headcount w/ robots	4
headcount reduction	32
annual labor savings (2 shifts)	$ 2,820,318

TOTALS

Total # of robots	84
Total robot investment	$ 5,880,000
Annual labor savings	$ 8,460,955

Total direct headcount w/o robots	514
Total direct headcount w/ robots	418
% labor reduction	19%

		discounted labor savings	cumulative
2nd year labor savings	$ 8,799,393	$ 7,999,448	$ 16,460,403
3rd year labor savings	$ 9,151,369	$ 7,563,115	$ 24,023,518
4th year labor savings	$ 9,517,424	$ 7,150,581	$ 31,174,100
5th year labor savings	$ 9,898,121	$ 6,760,550	$ 37,934,649

Payback period	**0.69 years**

Payback period	**0 years and**
	8 months

Program Life	5 years
Cost of Capital (target)	15.0%
Cost of Capital (actual)	10.0%
Discounted labor savings	$ 37,934,649
Added investment	$ 5,880,000
ΔNPV	**$ 32,054,649**

* Modified for use in this thesis

NA-AFC Automation Trade-off Analysis for Open Mold Fiberglass
Looking at robotic spraying versus manual spraying

Mexico

Annual Volume	25000
Hours per day/shift	7.3
Shifts per day	2
Days per year	235
Hours per year	3431
NWR	7.29

Cost of a robot	$ 70,000
man-year costs	$ 8,914

# of panels per car	32
# of panels per hour	233.17

LABOR COSTS

Fiberglass hourly wage in Ramos	$ 3.12
Hourly cost of benefits	$ 1.17
Total hourly labor costs	$ 4.29
Total man-year labor costs	$ 8,914

Labor cost breakdown		
72.8%	wages	
27.2%	benefits	
0.374	ratio of benefits/wages	

Assumptions:
1. Location = Ramos
2. Supplier on local supply campus - non-union workforce
3. Robots require 1 person per 14 robots for nightly clean-up/PM
4. 3.5 minute process time for all spray operations
5. Robots require 1 person per 14 robots as Technician
6. Cost of capital is equal to 2002 GMVO return on assets*

GEL COAT

spray time per mold	3.5
# of molds per robot	17.14
fractional # of robots	13.60
whole # of robots	28
added investment	$ 1,960,000

Direct headcount w/o robots	36
Direct headcount w/ robots	4
headcount reduction	32
annual labor savings	$ 285,257

BARRIER COAT

spray time per mold	3.5
# of molds per robot	17.14
fractional # of robots	13.60
whole # of robots	28
added investment	$ 1,960,000

Direct headcount w/o robots	36
Direct headcount w/ robots	4
headcount reduction	32
annual labor savings	$ 285,257

GLASS CHOP

spray time per mold	3.5
# of molds per robot	17.14
fractional # of robots	13.60
whole # of robots	28
added investment	$ 1,960,000

Direct headcount w/o robots	36
Direct headcount w/ robots	4
headcount reduction	32
annual labor savings	$ 285,257

TOTALS

Total # of robots	84
Total robot investment	$ 5,880,000
Annual labor savings	$ 855,771

Total direct headcount w/o robots	514
Total direct headcount w/ robots	418

		discounted labor savings	cumulative
2nd year labor savings	$ 890,002	$ 809,093	$ 1,664,864
3rd year labor savings	$ 925,602	$ 764,961	$ 2,429,825
4th year labor savings	$ 962,626	$ 723,236	$ 3,153,061
5th year labor savings	$ 1,001,132	$ 683,786	$ 3,836,847

Payback period	**6.87 years**

Payback period	**6 years and 10 months**

Program Life	5 years
Cost of Capital (target)	12.0%
Cost of Capital (actual)	10.0%
Program labor savings	$ 3,836,847
Added investment	$ 5,880,000
ΔNPV	**$ (2,043,153)**

* Modified for use in this thesis